Multi-Objective Optimal Operation of Urban Water Supply Systems

By

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Abstract

The world's water resources are rapidly deteriorating due to the combined effects of global warming, climate change, population growth and fast development, posing new challenges to water resources managers. Conflicting objectives and expectations of various stakeholders have led to increasing interests in the consideration and resolution of multiple social, economic, environmental and supply sustainability objectives in the management of water supply systems, especially during extended dry periods. This study attempted to develop and assess the potential of a generic decision support framework to assist in evaluating alternative operating rules for multi-purpose, multi-reservoir urban water supply systems. The multi-objective outranking approach which facilitated the incorporation of stakeholder preferences in the decision making process is a main focus area in this research.

The main elements of the framework are illustrated on a case study of the Melbourne water supply system, demonstrating its capabilities for evaluating alternative operating rules under single or group decision-making situations. Eight performance measures (PMs) were identified under four main objectives to evaluate the system performance related to sixteen pre-selected alternative operating rules. Three major stakeholder groups, namely, resource managers, water users and environmental interest groups were represented in hypothetical decision making situations. An interviewer-assisted questionnaire survey was used to derive stakeholder preferences on PMs in terms of preference functions and weights as required by the PROMETHEE/GAIA method and its computer software tool Decision Lab 2000. A total of 97 personnel selected from Melbourne Water and Victoria University participated in the survey expressing their preferences on the eight PMs. Finally, an overall ranking for alternative operating rules is obtained together with other output results, which focused on the best compromises between the objectives considered. The method yields reliable and robust results in terms of varying group compositions considered in the case study.

The major innovation of this project is the development of a transparent and intuitive multi-objective decision support framework that has potential to be developed for evaluating alternative operating rules for urban water supply systems.

Declaration

I, Prashanthi Nirmala Kodikara, declare that the PhD thesis entitled 'Multi-Objective Optimal Operation of Urban Water Supply Systems' is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Prashanthi Nirmala Kodikara
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Following individuals and institutions also deserve special mention for their contributions to this dissertation and their support, which is gratefully acknowledged:

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Finally, in recollecting the memories of past few years, I am delighted to see the sheer scale of excitement, frustration and rich rewards that this research project has brought me, and hopeful that I would have an opportunity to share this wealth of experience and knowledge with others.

Table of Contents

Chapter 1: Introduction

Chapter 2: Multi-Criteria Decision Aiding and Decision Support Systems

Chapter 3: Evaluation of Alternative Operating Rules for Urban Water Supply Systems

Chapter 4: Elicitation and Modelling of Stakeholder Preference Parameters

Chapter 5: Sensitivity Analysis, Robustness Measures and Derivation of Optimum Operating Rules

Chapter 6: Conclusions and Recommendations

APPENDICES

List of Tables

List of Figures

Abbreviations

The following list of abbreviations is used throughout this thesis. The other abbreviations, which were used only in particular sections or chapters are defined in the relevant sections or chapters.

AAD	Average Annual Demand
DM	Decision Maker
DMCDA	Discrete Multi-Criteria Decision Aiding
DMG	Decision Making Group
DR	Duration of Restrictions - Maximum consecutive duration of any form of restrictions during the simulation period
DRP	Drought Response Plan
DSSs	Decision Support Systems
ELECTRE	The multi criteria outranking method ELimination Et Choix Traduisant la REalite'
ENs	Environmental interest groups
EN$_{rep}$	Representative Environmentalist
FR	Frequency of Restrictions
GAIA	Geometrical Analysis for Interactive Assistance
GDM	Group Decision Making
GDSS	Group Decision Support Software
Gl	Gigalitre = 1 million cubic metres = 1000 Ml
HR	Hydropower Revenue
LRC	Lower Rule Curve
MAUT	Multi Attribute Utility Theory
MCDA	Multi-Criteria Decision Aiding
Ml	Megalitre = 1 million litres = 1000 cubic metres
Ml/d	Megalitres per day
MPF	Minimum Passing Flow
MS	Total System Minimum Storage
MW	Melbourne Water
PC	Pumping and treatment Costs
PF	Preference Function
PMs	Performance Measures
PROMETHEE	Preference Ranking and Organization METHod for Enrichment Evaluation
REALM	REsource ALlocation Model
RF	River Flows
RMs	Resource Managers
SR	Monthly Supply Reliability
TSS	Total System Storage
URC	Upper Rule Curve
VU	Victoria University
WL	Worst Level of Restrictions
WTP	Winneke Treatment Plant
WU$_{rep}$	Environmentalists
WUs	Water Users

Chapter 1: Introduction

1.1 Background

Over the past 40 years, water resources managers all over the world have extended their responsibilities into numerous water challenges such as improving the quality and quantity of water provided to the public, maintaining healthy eco-systems and waterways, and nursing the nations through severe droughts. However, it is acknowledged that these challenges intensify on a continuous basis in urban areas, since the world's water resources are rapidly deteriorating due to the combined effects of global warming, climate change, population growth and fast development. While these effects are becoming more and more apparent, there are tough new challenges for water resources managers to explore the ways of urgently recovering and managing this precious and severely threatened resource, water, both in terms of quality and quantity.

Galloway (2005) points out that, if any attempt is made to rate the disciplines by challenges they face, water resources would be at or near the top since for many people in the world, water is becoming an unfulfilled basic need. By 2025, two- thirds of world's population is likely to live in countries with moderate or severe water shortages. A recent report by the United Nations (2003) claims that, an estimated 1.1 billion people lack access to safe drinking water; 2.5 billion people have no access to proper sanitation; and more than 5 million people die each year from water-related diseases. The potential for conflict is obvious in this situation. Therefore, with rising stakeholder concerns over the possible risks to the limited water resources, it is also necessary to recognise a wide variety of stakeholders who would like to participate in water management issues.

For Melbourne, it is predicted that the water supplies could be reduced by 20 per cent by 2050, and the implications of potential climate change for Melbourne's water resources were identified as (Howe et al. 2005):

- Increased average and summer temperatures
- Reduced rainfall

- Reduced streamflows, and
- More extreme events with more hot days, more dry days and increased rainfall intensity during storm events.

While Australia has been identified as one of the most affected regions of climate change, Melbourne has already recorded a profound impact on its water supplies in terms of reduced rainfalls and streamflows, increased average temperatures and more extreme events. Among more than 150 years of rainfall records, Melbourne area registered a very severe drought year ending in May 2007 (with the lowest rainfall record in history), on top of a decade long extended dry period. Also a statement on a recent joint project report (yet to be released), 'Infrastructure and Climate Change Risk Assessment for Victoria', prepared for the Victorian Government by Commonwealth Scientific and Industrial Research Organization (CSIRO), Consultants Maunsel (Australia) and Lawyers Phillips Fox endorses the adverse effects of climate change on Melbourne's water supplies as:

> "*We're experiencing that in a number of ways: with the driest year on record in Melbourne; the fact that May has been quite considerably warmer than average; and that we're now down at 29.3 per cent of water availability in Melbourne. Of course I'm not saying any of that is solely due to climate change, but climate change is now clearly having an impact on our lives*"
>
> Paul Holper, Project Leader (The Age 16 May 2007).

As a growing city Melbourne is also experiencing its biggest population growth surge since the 1960s, with its population now increasing by almost 1000 a week and dominating that of any other Australian capital city (The Age 28 February 2007). According to the Australian Bureau of Statistics (http://www.abs.gov.au), Melbourne added about 49,000 people in the year to June 2000; far more than Sydney (37,000), Brisbane (29,500) or Perth (30,000). As population grows, there could be significant increases in demand for water, exerting more pressure on water supply systems.

It has been long recognized by the urban water industry in Melbourne, that their ability to meet future demands for water is doubtful especially due to the combined effects of climate change, global warming, fast development and increase in population in urban areas. It is therefore necessary to identify possible options to deal with effective water resources management, and to suggest detailed methodologies while understanding the problems at their root levels.

Decision analysis is recognised as a disciplined approach for managing urban water resources systems for particular uses that require interactive dialogue among all stakeholders who have different priority objectives (Abrishamchi et al. 2005; Cai et al. 2004). Conflict resolution in the context of water resources management usually involves the affected stakeholders in solving the issues surrounding the dominance of one water use over another; the rights of natural systems and the rights of water users. Therefore, the decision analysis methodologies that are capable of handling conflict resolution are particularly useful tools in analysing decision problems that extend to the level of accommodating the stakeholder preferences.

1.2 Significance of the Research

With the construction of new large-scale water storage projects at a virtual standstill in the developed countries, along with an increasing opposition to large storage projects in developing countries, attention is focussed on improving the operational effectiveness and efficiency of existing reservoir systems (Labadie 2004).

The Water Resources Strategy Committee for Melbourne Area (Water Resources Strategy Committee 2001) also identified the possible scarcity of water for Melbourne and proposed four broad options to meet the future water demands up till 2050:

- Seek new water sources,
- Reduce demand,
- Substitute with recycled water, and
- ‘Squeeze more from the current supply system’- the terminology used by the above Committee.

However, in looking for new water sources, the outcomes of the key research together with customer preference studies ruled out the option of building new dams and diversion weirs as a guiding principle for Melbourne (Water Resources Strategy Committee 2002a; 2002b). Various measures have been taken by the urban water authorities to reduce demand through education, awareness and conservation measures, which have slowed down the rate of increase in water use. For example, in Melbourne, the demand management measures have seen a reduction of rate of increase from 3% in the 1980s to 1% in 2000 (Water Resources Strategy Committee 2001). The use of desalinated water, recycled water and urban and roof runoff are also the other areas that are currently under consideration.

Apart from the above direct supply and demand options, the efficient and optimal operation of existing water supply systems pave the way to 'squeeze more from the current supply system'. The optimal operation is achieved through optimum operating rules. These operating rules, which are commonly used by urban water authorities, define the severity and timing of water restrictions and the spatial distribution of storage volumes of the reservoirs in the water supply system (Perera et al. 1999).

Mathematical modelling has been widely used in the past for determining the optimum operating rules for multi-reservoir water supply systems, addressing the decision problem with respect to a single objective. However, in reality, the decision problem is often associated with many objectives (often conflicting) related to social, economic, environmental and functional requirements of the stakeholders. Many solutions could exist depending on the priority objectives of these stakeholders. Once the Decision Maker (DM) has identified the priority objectives, the optimum solution would be a fair compromise between these objectives.

Recently, the stakeholder preferences had played a vital role in developing strategies for water resources planning (Water Resources Strategy Committee 2002a; 2002b). Though the previous studies have given due consideration to the uncertainties involved in the streamflow and demand conditions, no allowance has been given to the uncertainties involved in the preferences of the stakeholders. The literature review conducted in preparing this thesis suggests that, Multi-Criteria Decision Aiding (MCDA) techniques provide a considerable enrichment to the poor rationality of the single objective optimisation problems (Pomerol and Barba-Romero 2000; Rogers et al. 2000; Vincke 1992; Zoints 1990). Available MCDA methods so far differ with each other in the quality and quantity of additional information they request, the methodology they use, their user-friendliness, the sensitivity tools they offer, and the mathematical properties they verify.

In discrete case of MCDA, the problem is defined by a finite number of alternatives and a family of performance measures (arising from different perspectives of the DM) on which the alternatives are evaluated. The problem could also have a third dimension if it involves multiple DMs and/or uncertainties in the performance measure evaluations (Mareschal 1986). The outranking methods belonging to the discrete MCDA category have seen a rapid development during the last decade because of their adaptability to the poor structure of most real decision situations, and are becoming more popular among the DMs due to the greater potential for interaction and negotiation.

This study was undertaken to strengthen the decision analysis module to derive optimum operating rules for urban water supply systems in a generic decision support framework proposed in a previous study. The details of this previous study (Perera et al. 1999) are given in Section 2.6. The main focus of the current study was to critically analyse the social, economic, environmental and supply sustainability aspects of managing urban water supply systems and to systematically blend the stakeholder preferences in the decision process.

The concept of the proposed decision support framework is illustrated in Figure 1.1. It mainly provides the planners (or DMs) with:

- The evaluation of alternative operating rules using various system Performance Measures (PMs)**,** and
- Further facilitating the stakeholder participation in the decision process by incorporating the stakeholder preferences.

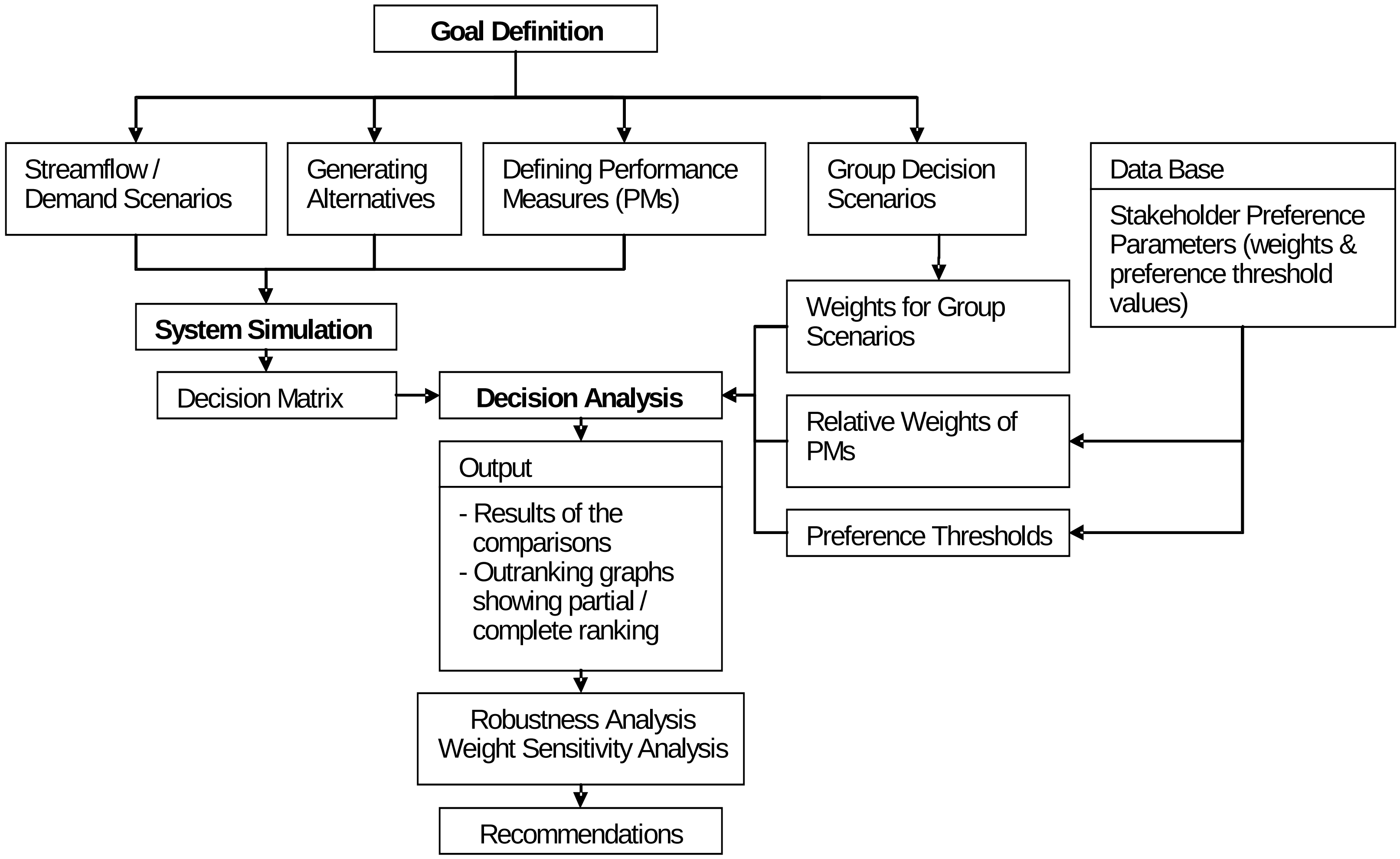


Figure 1.1: Proposed Decision Support Framework for Determining Optimum Operating Rules for Urban Water Supply Systems

The proposed framework given in Figure 1.1 is developed as a generic system and a case study example is demonstrated on deriving optimum operating rules for the Melbourne water supply system. The water supply planning simulation model REALM - REsource ALlocation Model (Perera and James 2003; Perera et al. 2005) provides the values of PMs corresponding to each operating rule (decision matrix) under defined streamflow and demand scenarios. Discrete MCDA approach is then used with the decision matrix to analyse and rank the operating rules (i.e. decision analysis) with DMs' preference information, and to examine sensitivity and robustness of the results. With this framework, it is also possible to analyse the decision problem with a Decision-Making Group (DMG) with appropriate representations from stakeholder groups. The current study will emphasise more on the decision analysis module based on MCDA.

This thesis contains the research work carried towards the development and illustration of the proposed framework shown in Figure 1.1. Chapter 2 includes the findings of a literature survey conducted on available MCDA methods/software and decision support systems; Chapter 3 discusses the past experiences of water supply system operations and evaluation of alternative operating rules; Chapter 4 explains a detailed methodology for stakeholder preference elicitation and modelling; Chapter 5 discusses the derivation of optimum operating rules and the sensitivity/robustness of the results; and Chapter 6 lays down the conclusions and the recommendations of the study.

1.3 Aims of the Study

The efficient and optimal operation of existing water supply systems is recognized as one of the safest options to provide reliable and cost effective water supply to urban areas that is environmentally sustainable in the long run. The aim of this research is to develop a decision support framework for planners to provide an insight into the problem of evaluating alternative operating rules in determining the optimum operating rules to manage the existing urban water supply systems considering:

- Streamflow/demand scenarios
- Competing objectives, and
- Stakeholder preferences on objectives

This framework will facilitate the recommendation of an overall ranking for alternative operating rules to ensure the efficient and effective management of the systems under a range of short and long term planning conditions, and drought conditions, while focusing at a best compromise between several objectives. The stakeholder preferences on various objectives together with system performance evaluations will rank the alternative operating rules according to their best compromising nature.

A case study example on the Melbourne water supply system is also demonstrated, which finally leads to a compromising decision among major stakeholder groups of the Melbourne system. Long-term social, economic, environmental and supply sustainability aspects are taken into consideration when generating the relevant objectives for this specific case study. The four main objectives considered are to:

(1) Maximize the level of service to the water users

(2) Minimize the costs and maximize the revenue

(3) Minimize the effects on environment and

(4) Maximize the supply sustainability

The inclusion of many diversified viewpoints of three major stakeholder groups in the Melbourne water supply system, namely, resource managers (RMs), water users (WUs), and environmental interest groups (ENs), in the decision is facilitated by a detailed preference parameter elicitation and modelling process conducted on representatives from RMs, WUs and ENs. The potential alternative operating rules are finally analysed and compared against each other, using:

- PM evaluations that summarize the system’s performance under the above objectives, and
- The modelled stakeholder preference parameters

The major innovation of this project is the development of an interactive decision support framework to objectively determine the optimum operating rules for urban water supply systems considering a range of PMs identified by the affected stakeholder groups.

1.4 Research Methodology

The key tasks involved in achieving the aims described in Section 1.3 are as follows:

1. Selection of an appropriate MCDA method for the decision module.
2. Identification of relevant objectives, PMs and alternative operating rules.
3. Evaluation of alternative operating rules.
4. Design a procedure to elicit preference judgments on PMs from various stakeholder groups.
5. Analysis of preference judgment data and modeling the stakeholder preference parameters.
6. Derivation of optimum operating rules for the Melbourne water supply system.
7. Conducting sensitivity and robustness analyses on optimum operating rules of the Melbourne water supply system.

Task (1) follows a critical review of the available literature on MCDA methods/software, some of the decision support systems with built-in MCDA tools and their applications. The tasks (2) - (7) are demonstrated on the case study example on Melbourne water supply system. However, the decision support framework that is proposed in this study (Figure 1.1) can be used for any urban water supply system. A brief description of each of the above tasks is given below.

Task 1 - Selection of an appropriate MCDA method for the decision module

There are many governing concerns to this key decision, but yielding results of acceptable reliability was considered as a fundamental requirement. It was aimed at understanding the decision problem and selecting one or few ‘best compromising’ operating rules for a system among several pre-selected alternative operating rules rather than judging the suitability of all the alternatives in the selected set. Therefore, the focus was drawn more towards to ‘select’ the optimum operating rules, rather than attempting to arrive at a ‘precise ranking’ of all the feasible alternatives.

From the DM’s point of view, ease of use/simplicity (i.e. time and effort required of the DM to reach a conclusion) and understandability of the method are considered important. In addition to the above requirements, the quantity and quality of information (input data) needed and difficulty in obtaining them, ability to handle uncertainties and availability of user-friendly software were also concerns. These issues were considered in selecting the MCDA method/software for the decision module.

Task 2 - Identification of relevant objectives, PMs and alternative operating rules

First, the various long term planning objectives and alternative operating rules were identified through the literature search and discussions with the officials of the Urban Water Planning Division of Melbourne Water (MW). Then, a complete (exhaustive) and non-redundant set of PMs covering a range of social, economic, environmental and supply sustainability aspects of the Melbourne water supply system was defined to include the important perspectives of the system. In all, four objectives and a set of eight PMs, which summarised the Melbourne water supply system's performance under the specified objectives, were defined to evaluate the alternative operating rules.

Alternative operating rules for Melbourne water supply system were generated by considering the variations to the current operating rules in terms of the demand restriction policy, the pumping/treatment of water at Sugarloaf reservoir, the hydropower generation at Thomson and Cardinia reservoirs and the minimum passing flows in Yarra river and Thomson river. The details of these alternative operating rules are given in Section 3.5.2.

Task 3 - Evaluation of alternative operating rules

As suggested in the proposed framework given in Figure 1.1, the system performance under each of these alternative operating rules was measured and evaluated in terms of the pre-defined PMs using REALM (REsource ALlocation Model) water supply simulation software (Perera and James 2003; Perera et al. 2005). The case study example was illustrated using a single streamflow/demand condition.

Task 4 - Design a procedure to elicit preference judgments on PMs from various stakeholders

Preference elicitation on PMs from various stakeholders was a major task in this research study. Different MCDA methods require different types of information as inputs. Therefore, the type and amount of the required input information largely depend on the MCDA method chosen. Once the MCDA method has been selected, the preference judgments required by the chosen MCDA method/software were collected through a carefully designed questionnaire and personal interviews with three key stakeholder groups (i.e. RMs, WUs and ENs).

Initially, the interview procedure was pilot-tested with eight staff members from Victoria University (VU). Based on the findings of the pilot survey, the necessary adjustments and refinements were made to the questionnaire and to the interview procedure, before the full survey was carried out.

The RMs group comprised middle to senior managers of the Urban Water Planning Division of MW. As explained later in Section 4.5.1, due to time and cost limitations of this study, the WUs and ENs groups were represented by selective samples from VU staff and post-graduate students. The WUs group represented the residential water users of the Melbourne's three retail water companies; City West Water (CWW), Yarra Valley Water (YVW) and South East Water (SEW) and comprised eighty-five (85) staff members from VU. The ENs group included six (6) academic staff members/post-graduate students from VU, who are working on environmental sustainability matters.

Task 5 - Analysis of preference judgment data and modeling the stakeholder preference parameters

The preference judgment data were analyzed with the aid of quantitative statistics and then the preference parameters were modeled in order to provide the appropriate representations from the different stakeholder groups in the DMG. These modeled preference parameters of various stakeholder groups combined with a single matrix of the PM evaluations of alternative operating rules, facilitated the decisions based on the agreed representations of the stakeholders' viewpoints in Group Decision-Making (GDM) situations.

Task 6 - Derivation of optimum operating rules for the Melbourne water supply system

The evaluations of alternative operating rules (derived in Task 3) were then combined with the modeled preferences of stakeholder groups (derived in task 5) to arrive at a compromised ranking of the alternative operating rules. The results were first examined under all possible single DM situations and a GDM situation with all RMs. Then the final rankings were derived for two hypothetical GDM situations separately with varying participations from each stakeholder group.

Task 7 - Sensitivity analysis and robustness measures on optimum operating rules

Finally, the sensitivity analysis was carried out for results under both GDM situations by varying the voices of different categories of stakeholders. The robustness analysis indicated that the range of weightings (of the different actors in the group) did not result in a modification of the rankings of the alternative operating rules.

1.5 Layout of the Thesis

The layout of the thesis is organised as shown in Figure 1.2. The first chapter presents the issues related to water resources in general, and over the years, how these issues have made an impact on the urban water supplies. It also identifies the significance of research (i.e. the need for optimal operation of urban water supply systems), and proposes a conceptual framework for decision support. The aims of the study and a detailed approach to achieve these stipulated aims are also presented in this chapter.

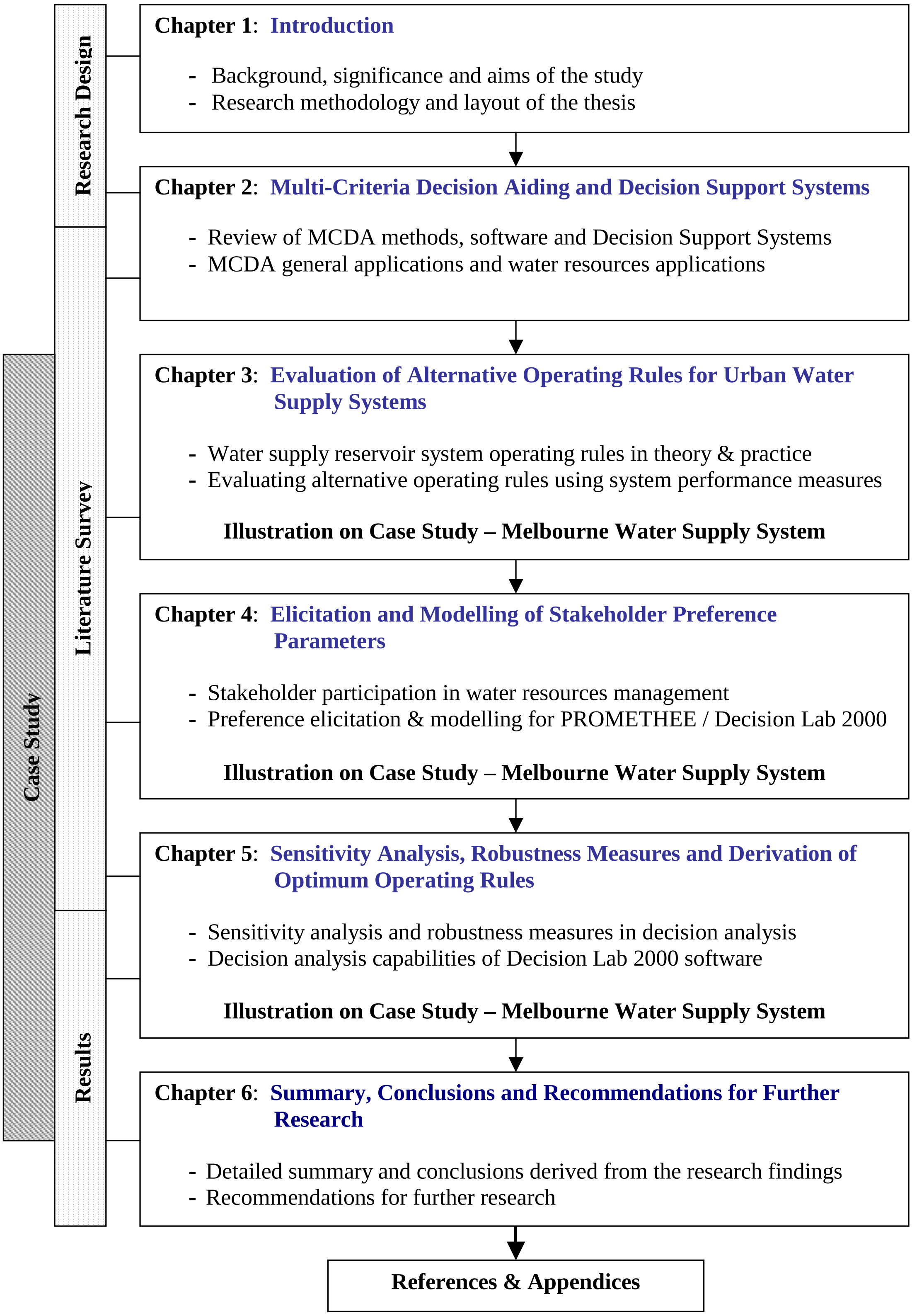
The second chapter provides a background to the decision analysis practices in general and includes a critical review of the MCDA applications in water resources management and other fields. A detailed literature survey on available MCDA methods and software is also presented in this chapter. Thereby, the first two chapters set the need and cover the research design for the study. It should be noted that, although the bulk of the literature survey findings are concentrated in Chapter 2, parts of the literature survey findings are also spread through Chapters 3, 4 and 5, where it was particularly necessary to discuss the applications related to the case study.

The third chapter explains the development of effective management practices in water supply reservoir systems operations, how the alternative operating rules could be evaluated with the aid of system PMs, and a description of the RELAM water supply simulation software. The case study example on Melbourne water supply system is introduced in this chapter, illustrating the evaluation of alternative operating rules using eight system PMs. However, as shown in Figure 1.2, the case study application of the proposed methodology is spread across Chapters 3, 4, 5 and 6.

The fourth chapter explains the current trends in stakeholder participation in water resources decision-making, the preference elicitation for MCDA outranking methods, the preference parameters required by the chosen MCDA method and software tool for this study, PROMETHEE/*Decision Lab 2000*. The case study example is also presented in this chapter with a detailed preference elicitation and modelling process conducted on key stakeholder representatives of the Melbourne water supply system.

The fifth chapter discusses the sensitivity analysis and robustness measures related to decision analysis in general and the built-in tools provided in the *Decision Lab 2000* software for sensitivity and robustness analysis. This chapter also includes the identification of an optimum operating rule for Melbourne water supply system amongst the alternatives considered in the case study. Subsequently, the sensitivity and robustness of the results are checked against the possible variations to the GDM settings.

Finally, a summary of the thesis and the main conclusions of the study are presented in the sixth chapter along with the recommendations for future work.



Chapter 1: **Introduction**

- Background, significance and aims of the study
- Research methodology and layout of the thesis

Chapter 2: **Multi-Criteria Decision Aiding and Decision Support Systems**

- Review of MCDA methods, software and Decision Support Systems
- MCDA general applications and water resources applications

Chapter 3: **Evaluation of Alternative Operating Rules for Urban Water Supply Systems**

- Water supply reservoir system operating rules in theory & practice
- Evaluating alternative operating rules using system performance measures

Illustration on Case Study – Melbourne Water Supply System

Chapter 4: **Elicitation and Modelling of Stakeholder Preference Parameters**

- Stakeholder participation in water resources management
- Preference elicitation & modelling for PROMETHEE / Decision Lab 2000

Illustration on Case Study – Melbourne Water Supply System

Chapter 5: **Sensitivity Analysis, Robustness Measures and Derivation of Optimum Operating Rules**

- Sensitivity analysis and robustness measures in decision analysis
- Decision analysis capabilities of Decision Lab 2000 software

Illustration on Case Study – Melbourne Water Supply System

Chapter 6: **Summary, Conclusions and Recommendations for Further Research**

- Detailed summary and conclusions derived from the research findings
- Recommendations for further research

References & Appendices

Figure 1.2: Layout of the Thesis

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Chapter 2: Multi-Criteria Decision Aiding and Decision Support Systems

2.1 Introduction

Since the beginning of the mankind on earth, there is evidence of countless human decision situations related to real life problems with many desirable attributes. These attributes are often referred to in literature as criteria or Performance Measures (PMs) upon which various decision situations are evaluated. The idea of contradictory criteria has also existed in popular culture since time immemorial, generally appearing in the form of proverbs and fables (Pomerol and Barba-Romero 2000) and since then, people have been trying to master the craft of decision making by using their intuition. The first known recorded information on multi-criteria decision making, as quoted by many authors (e.g. Zelany 1982; Zoints 1990), is a letter, more than 200 years ago, from the well-known American philosopher Benjamin Franklin (1706-1790) to the British scientist Joseph Priestly (1733-1804). Priestly asked Franklin, a way to make up his mind, when strong and numerous arguments presented themselves for both of two proposed lines of conduct. The reply letter sent by Franklin is presented below:

> *London, Sept 19, 1772*
> *Dear Sir,*
>
> *In the affair of so much importance to you, wherein you ask my advice, I cannot, for want of sufficient premises, advise you what to determine, but if you please I will tell you how. When those difficult cases occur, they are difficult, chiefly because while we have them under consideration, all the reasons pro and con are not present to the mind at the same time; but sometimes one set present themselves, and at other times another, the first being out of sight. Hence the various purposes or information that alternatively prevail, and the uncertainty that perplexes us. To get over this, my way is to divide half a sheet of paper by a line into two columns: writing over the one Pro, and other Con. Then, during three or four days consideration, I put down under the different*

> *heads short hints of the different motives, that at different times occur to me, for or against the measure. When I have thus got them all together in one view, I endeavour to estimate their respective weights; and where I find two, one on each side, that seem equal, I strike them both out. If I find a reason pro equal to some two reasons con, I strike out the three. If I judge two reasons con equal to three reasons pro, I strike out five; and thus proceeding, I find at length where the balance lies; and if, after a day or two of further consideration, nothing new that is of importance occurs on either side, I come to a determination accordingly. And, though the weight of the reasons cannot be taken with the precision of algebraic quantities, yet when each is thus considered, separately and comparatively, and the whole lies before me, I think I can judge better, and am less liable to make a rash step, and in fact I have found great advantage from this kind of equation, and what might be called moral or prudential algebra.*
>
> *Wishing sincerely that you might determine for the best, I am ever, my dear friend, yours most affectionately,*
>
> *B. Franklin*

Franklin called it 'moral or prudential algebra' and this represents one of the first systematic methodologies for solving problems characterized by multiple criteria. According to Zelany (1982), most of the basic ingredients of Multi-Criteria Decision Aiding (MCDA) can be found in the above letter; the weighting of criteria importance, the trading off of one criteria to another, the notion of the balanced decision and even the interaction between human judgment and a formal model.

Pomerol and Barba-Romero (2000) state that the research into economics which took place at the end of the nineteenth century and the beginning of the twentieth century are one of the sources of inspiration for the domain of multi-criteria analysis. Zoints (1990) sees the first modern treatment of multiple criteria decision making as that of Simon (1958). He reports that Simon's work on aspiration levels, and then searching until one finds a solution that achieves the target or aspiration levels. If many solutions exist, then the aspiration levels are tightened; if no solution exists, then the aspiration levels are relaxed.

From 1950's onwards, there had been a large number of refined MCDA methods developed and they differ with each other in the required quality and quantity of additional information, the methodology used, the user-friendliness, the sensitivity tools used, and the mathematical properties they verify. While there are ongoing efforts to establish MCDA methods in professional contexts (Brans and Mareschal 2005; Munda 2005) claiming that these methods provide systematic and transparent approaches that increase objectivity and reliability of results, the opponents to the use of these methods argue that the MCDA methods are prone to manipulation, are very technocratic, and provide a false sense of accuracy (Janssen 2001).

With the growing complexity of the decision situations, the application of MCDA methods often requires a considerable amount of computation. Exploring and analysing a particular problem using many MCDA methodologies, therefore, had become hardly imaginable without the use of specialised software. With the wide variety of MCDA software available today, this software built into an interactive Decision Support System (DSS) could provide the Decision Maker (DM) with structured solutions to the problems with multiple objectives, through an interactive learning process.

This chapter presents a brief background and the history of MCDA, and highlights the importance, the relevance, and the versatility of MCDA in many decision situations as encountered in the literature. Firstly, the multiple objective aspects of operational decisions are discussed together with a presentation of the key concepts of MCDA. Secondly, a review of available MCDA techniques, which have been progressively developed and modified, is presented together with a variety of real-world applications. Then an overview of the current MCDA software is presented with practical examples on the MCDA software built into DSSs with particular focus on water resources management applications. Chapter 2 concludes with the methodology for selection of an MCDA technique and software for this study.

2.2 Multiple Objectives in Decisions

Many decades ago, the natural decision making process has been strongly based on the comparison of different points of view (i.e. criteria or PMs), some in favour and some against a certain decision. Contrary to this very natural observation, the operations research presented its optimisation model, which is based on the maximisation or minimisation of a single objective function, subject to some constraints. Pomerol and Barba-Romero (2000) claim that these ‘single objective optimisation’ models quickly gained the acceptance of the scientific population due to its strong theoretical foundation. Probably due to this reason, the ‘optimisation’ paradigm is still considered to be very powerful and is dominant in the work of many researchers. However, in this approach, one main practical difficulty lies in attempting to summarise all the points of view related to the desired results of the decision at hand in only one objective function. Another drawback of ‘optimisation’ modelling from the human point of view is its lack of realism without being able to present an effective framework to deal with the uncertainties of the world and the subjectivity of DM’s values and preferences (Slovic 1981). Pomerol and Barba-Romero (2000) also state that:

> “including *the criteria in the function to be maximised or in the constraints is not only an artifice, however conceptually admissible, but also harmful to the decision process since it prevents intervention of the decision maker and makes choices highly rigid.*”

Therefore, single objective optimisation has been considered as ‘far from reality’ by many researchers and practitioners (Brans 2002; Galloway 2005; Simon 1983) and for at least thirty years these researchers and practitioners have been attempting to address the multidimensional nature of the real decision problems.

Brans (2002) explains that in a socio-economic or human framework, a well-balanced decision should take into account, three poles of influence; rational, subjective and ethical poles. Most of the basic models of operational research are only considering the rational pole; no freedom is left to the DM, and no ethical aspects are considered. It is also not possible to ignore the fact that each real decision is the result of a compromise between several solutions which all have their advantages and disadvantages, depending on one's point of view. Since many conflicting aspects occur simultaneously, the solution is no longer an optimal one but a '*satisfactory*' one. While allowing for rationality and ethics, MCDA emphasizes the role of the subjective pole in the decision process, offering the DM, more freedom to consider several optimality points of view taking into account his/her emotionality and real-life experience. Multi-criteria modelling gives a freedom of judgement to the DM, which is obscured by single-criterion modelling. However, it is also reported that MCDA does not have inherent rationality. It often has the merits of realism, legibility and straightforwardness, but decision itself is, by definition, subject to political choice (Pomerol and Barba-Romero 2000).

Pomerol and Barba-Romero (2000) present a comprehensive and detailed history about the evolution of multi-criteria decision making, quoting that multi-criteria analysis acquired its own vocabulary and problem formulations by 1960, and with the gradual emergence of ideas in the sixties, multi-criteria analysis came into its own in 1972. From there onwards, numerous refinements were made to the methods and various avenues explored. In the field of MCDA, there are two clearly distinguished schools of thought, viz. a French school and an American school (Lootsma 1990). The French school is founded by Bernard Roy who mainly promoted the outranking concept for evaluating discrete alternatives (Roy 1968). The American school is inspired by the work of Keeny and Raiffa in 1976 on multi-attribute value functions and multi-attribute utility theory (Keeny and Raiffa 1976). The methods represented by both of these schools of thought are discussed in Section 2.4.

In practice, the applications in multi-criteria decision analysis stretch across many fields both at strategic and operational levels. These fields include public investment (e.g. Barba-Romero and Mokotoff 1997; Rogers et al. 2000b), resource allocation and management (e.g. Duckstein et al. 1994; Flug et al. 2000; Rigley 1989; Srinivasa Raju et al. 2000) and strategic decision (Rhodes et al. 2005; Siskos 1986).

Many years ago, when there had been adequate supplies of water to meet the various demands, the traditional way of managing water resources mainly focused on meeting a single objective, adopting the cost-benefit analysis or systems analysis approaches (Rogers et al. 2000b). Cost-benefit analysis attempts to quantify the prospective gains and losses from some proposed action, while systems analysis attempts to capture the interactions and dynamic behaviour of complex systems (Slovic 1981). Mathematical modelling has been widely used in such instances for determining the optimum operating rules for multi-reservoir water supply systems. These modelling approaches, ranging from simulation (Draper et al. 2004; Perera and James 2003; Sigvaldason 1976; Wurbs 2005; Zarriello 2002) to stochastic optimisation (Krancman et al. 2006; Lund and Ferreira 1996; Perera and Codner 1996; Tejada-Guibert et al. 1993; Wang et al. 2005), have addressed the decision problem with respect to a single objective.

Throughout the world today, however, there is a growing demand being placed on water resources for various purposes with different stakeholder groups perceiving multiple objectives in different ways. The rise in water demand in urban areas, coupled with possible adverse climate scenarios, increasing awareness on environmental issues and the lack of additional water resources pose new challenges to water resources managers. Conflicting objectives of stakeholders intensify these challenges, requiring the consideration of multiple objectives in terms of social, economic, environmental and supply sustainability perspectives for long-term operation of urban water supply systems. Then, the decision problem could have many solutions depending on the priority objectives. Once the DMs have set the priority objectives in terms of their preferences, the optimum solution should naturally be a fair compromise between these objectives. One reasonable way to strike a balance between these conflicting objectives is to incorporate the stakeholder preferences in the decisions (Rogers et al. 2004).

For many urban areas where water scarcity has been identified as a significant constraint to development, water strategies have been developed to ensure a concerted effort from all stakeholders towards a better management of available water resources under both long and short-term social, economic and environmental equity considerations (Water Resources Strategy Committee 2002b). In such situations, where multiple objectives that are characterized by a high degree of conflict come into play, MCDA could provide the DMs with promising results through exploration and learning. From this point of view, MCDA can also be considered as a tool for implementing political democracy (Munda 2005).

Operational decisions in water supply may be handled by a group of DMs, which could be formed to provide adequate representation from the stakeholder groups, in such a way that the final decisions would reflect the stakeholder views to an extent agreed upon by the group. The stakeholders usually include any individuals or organizations interested in the issue in question. In analysing the case study example, the Decision Making Groups (DMGs) comprising several DMs were considered and the details of these DMGs are included in Section 5.4.1.

2.3 Multi-Criteria Decision Aiding Techniques

The available decision making methods can either be considered as single objective or multiple objectives as illustrated in Figure 2.1. As also explained in Section 3.1, for water supply reservoir operations, the multi-objective optimisation approach gradually evolved to be popular, as opposed to single objective optimisation approach, with systems becoming more and more dynamic and complex. The multi-objective approach is applied to the case study problem dealt within this research, i.e. to determine the optimum operating rules for Melbourne water supply system, since it is a multi-purpose, multi-reservoir system that involves many competing objectives related to social, economic, environmental and other requirements of the stakeholders. Therefore, as also stated in Section 1.2, the literature survey included in here mainly focused on MCDA where the DM is faced with making one choice among several alternatives, i.e. discrete type of MCDA (shown shaded in Figure 2.1).

Among the large number of refined MCDA methods, devised and applied by both academics and professionals, the detailed literature review conducted during this study exclusively covered the discrete type of MCDA, where the problem is defined by a **finite number of alternatives** and a **family of performance measures** (arising from different perspectives) based on which the discrete alternatives are evaluated. However, a brief overview of the continuous MCDA methods and some applications of continuous MCDA methods in water resources management are also given below.

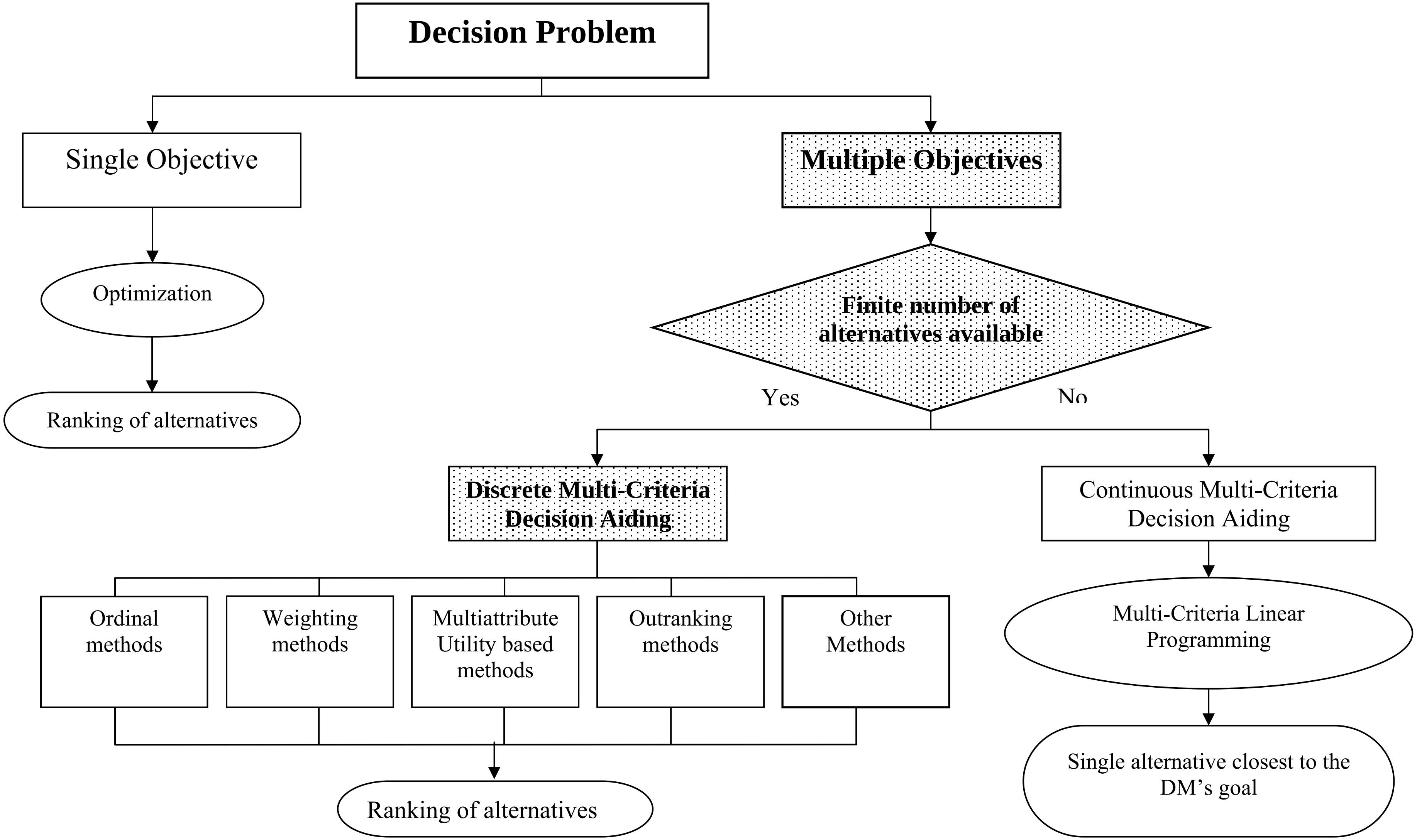

Figure 2.1: Decision Aiding Methods

2.3.1 Continuous MCDA Approach

The continuous MCDA methods use the multi-criteria linear programming to maximise or minimise a single objective function. The additional objectives are usually regarded as constraints. Pomerol and Barba-Romero (2000) note the existence of highly effective algorithms for solving this type of programs in single criterion case; these algorithms can, however be adapted to the multi-criteria case as well. Among the common methods to address the continuous MCDA problems, are the 'constraint method' by Cohon and Marks (1975) and 'goal programming' method by Charnes and Cooper (1961).

As a continuous MCDA approach, the 'constraint method' is recommended by Cohon and Marks (1975) for MCDA reservoir optimisation problems with fewer than four objectives. One objective, usually the most important one, is optimised as the primary objective. Any other objective is transformed into constraints and optimised as a secondary objective, simply by constraining the upper and lower bounds of the related PM. The 'constraint method' was employed by Westphal et al. (2003) in a decision support system for adaptive water supply management and McPhee and Yeh (2004) for sustainable groundwater management in Upper San Pedro River Basin, Arizona.

The 'goal programming' method, first introduced by Charnes and Cooper (1961) solves the continuous MCDA choice problems in linear programming by a search for a solution at minimal distance from a multicriterion goal, generally non-achievable, set by the DM. It arrives at an alternative closest to the DM's ideal goal by minimising the distance from the goal. Vincke (1992) lists the steps involved in goal programming as:

- Setting the values DM wishes to attain on each PM (these are related to the objectives)
- Assigning priorities (weights) to the objectives
- Defining (positive or negative) deviations with respect to these objectives
- Minimising the weighted sum of the deviations and
- Performing sensitivity analysis

As Vincke (1992) reports, the goal programming approach, first developed in the frame of linear programming, was extended to all other types of mathematical programs and was also rendered interactive. It had been a popular approach in the field of water resources management (Can and Houck 1984; Loganathan and Battacharya 1990; McPhee and Yeh 2004) with reported applications. Eschenbach et al. (2001) also employed goal programming within the *RiverWare* DSS and applied it to Tennessee Valley Authority operations.

2.3.2 Classification of Discrete MCDA Methods

Discrete Multi-Criteria Decision Aiding (DMCDA) methods have been classified into different groups by different authors (Pomerol and Barba-Romero 2000; Vincke 1992; Zoints 1990). One possible reason for this disparity is the fuzzy nature of the boundaries between these families (Vincke 1992). In this study the DMCDA methods were broadly considered under the following five categories:

- Ordinal methods
- Weighting methods
- Multi-attribute utility based methods
- Outranking methods and
- Other methods

Among the basic ordinal methods are the Borda's method (Black 1958), the Condorcet method (Condorcet and Marquis De 1785), the method of Bowman and Colantoni (Bowman and Colantoni 1973) and the lexicographic methods (Fishburn 1974). All these ordinal methods derive a final pre-order (i.e. ranking) for the set of alternatives by aggregating the individual pre-orders with respect to the PMs (or criteria).

The weighting methods, which have been abundantly used in numerous contexts, include the weighted sum method (Kepner and Tregoe 1965) and the weighted product methods (Pomerol and Barba-Romero 2000). However, in weighting methods, the results are largely dependant on the weights assigned to PMs, in contrast to ordinal methods making certain assumptions on the nature of the DM's preferences (Pomerol and Barba-Romero 2000). Though both of these methods (i.e. ordinal methods and weighting methods) do not provide adequate reliability in results for certain purposes, they are simple to apply, intuitive and very popular among DMs in the real world (Janssen 2001). Nevertheless, compared to the other analytical methods, research publications involving these elementary methods (i.e. ordinal and weighting methods) are rarely found in water resources management. Flug et al. (2000) applied the weighted sum method to evaluate nine discrete flow release alternatives in managing the Colorado River system below Glen Canyon Dam. Lin and Teng (1990) developed a model employing the weighted linear sum method to evaluate and select freeway interchange locations. They applied it to a case study in Taiwan where ten alternative locations were evaluated using 14 PMs categorised under four objectives.

Multi-attribute utility based methods and outranking methods together record a considerable number of DMCDA applications in the literature. Multi-attribute utility based methods assess and fit utility functions and probabilities to the performance measures (Keeny and Raiffa 1976), whereas the outranking methods are based on pair-wise comparison of alternatives (Roy 1968). However, these methods have their own advantages and disadvantages when applied to a particular decision problem. A detailed description of additive utility-based methods and outranking methods together with their applications, main advantages and disadvantages is presented in Section 2.4.

There are several other methods, which cannot be classified directly into any of the above categories, but still relying on various other MCDA methodologies. These methods, among others, include:

- Alternative comparison methods
- Methods involving distance from an ideal alternative (distance methods), and
- Permutation methods

The basic models on alternative comparison methods are the LINMAP (**LIN**ear programming technique for **M**ultidimensional **A**nalysis of **P**reference) method by Srinivasan and Shocker (1973a; 1973b) which is claimed to be a widely used standard method, and the Ziont's method (Zionts 1981). LINMAP is also considered as a method involving distance from an ideal alternative.

The popular methods that involve the distance from an ideal alternative include the TOPSIS (**T**echnique for **O**rder **P**reference by **S**imilarity to **I**deal **S**olution) by Hwang and Yoon (1981), AIM (**A**spiration-level **I**nteractive **M**odel) by Lofti et al. (1992) and Compromise Programming by Zelany (1982). Kheireldin and Fahmy (2001) applied Compromise Programming to evaluate Egypt's long term water strategies under several social, economic and environmental factors. They concluded that while this MCDA approach provided an efficient and systematic way of presenting tradeoffs among policy choices, it also rendered the transparency for negotiation and resolution of conflicts among different water stakeholders.

The original permutation method is proposed by Jacquet-Lagreze (1969) for the aggregation of individual opinions (Pomerol and Barba-Romero 2000). One of the established permutation methods is the QUALIFLEX (**QUALI**tative and **FLEX**ible assessment) method by Paelinck (1976) applied to a regional planning case study. The other applications of QUALIFLEX include an airport location problem (Paelinck 1977) and four case studies of urban resources management related to water supply, garbage disposal, public transport and public services (Ancot and Paelinck 1982).

In addition to the above-mentioned applications, the use of MCDA techniques has been demonstrated by a vast number of researchers/practitioners in water resources planning and management. They include Gershon et al. (1982) on dealing with multi-objective optimisation of river basin planning; Tecle et al. (1988), on selecting a best wastewater management alternative; Simonovic (1989), on formulating national water master plans; Cai et al. (2004), on conflict resolution in water resources planning; Duckstein et al. (1994), on ranking groundwater management alternatives; Netto et al. (1996), on design of long-term water supply in Southern France; and Abrishamchi et al. (2005), on urban water supply planning. All above methods deal with different decision-making situations. However, the choice of a method depends on the characteristics of the system being considered, on availability of data, and on the objectives and constraints specified (Barros et al. 2003).

2.4 Discrete Multi-Criteria Decision Aiding Techniques

Many researchers are in agreement that the MCDA techniques, when introduced to find an optimal solution, could provide a considerable enrichment to the poor rationality of the single objective optimisation problems (Brans and Mareschal 1990; Rogers et al. 2000b; Vincke 1992; Zoints 1990). They also believe that the interaction, which is encouraged throughout, i.e. from problem formulation to recommending a solution, contributes to the richness of the decision aid. The main stages in DMCDA are presented in Figure 2.2.

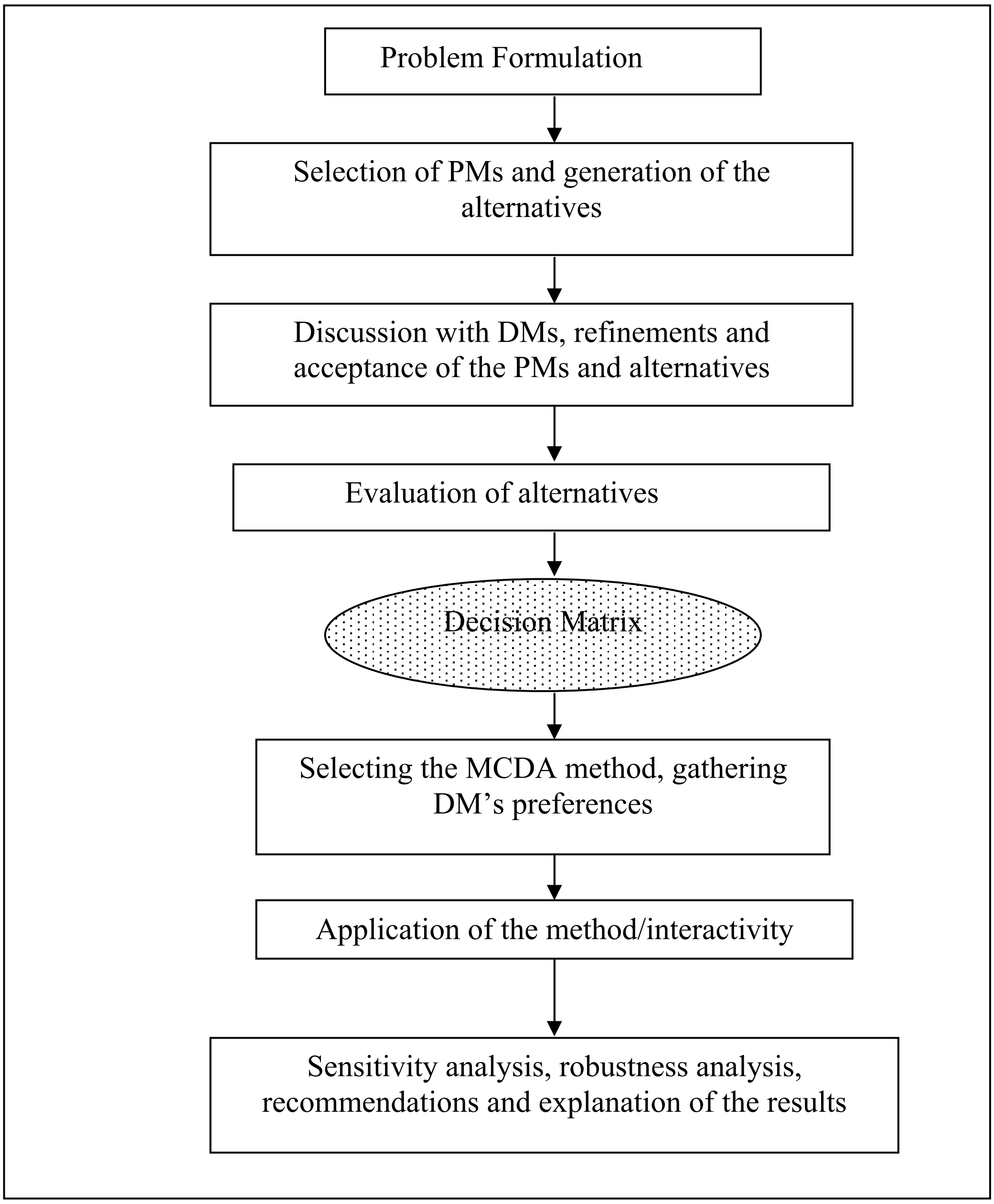

Figure 2.2: Various Stages in Discrete Multi-Criteria Decision-Aiding [Source: (Pomerol and Barba-Romero 2000)]

Consider a family of ***n*** PMs, [$f_1(.), f_2(.), \ldots\ldots, f_j(.), \ldots., f_n(.)$], to evaluate a finite set **A** of ***m*** possible alternatives, $\{a_1, a_2, \ldots a_i \ldots, a_m\}$. Table 2.1 presents the basic data of the multi-criteria problem in a decision matrix. The DM would like to look for the 'best choice' within the set **A**. All of the DMCDA methods start with the same decision matrix. However, the methods vary according to the additional information requested and the computational procedures followed to arrive at a solution ((Brans and Mareschal 2005).

Table 2.1: Decision Matrix

Alternative	$f_1(.)$	$f_2(.)$	.....	.....	$f_j(.)$	.....	.....	$f_n(.)$
a_1	$f_1(a_1)$	$f_2(a_1)$	.....	.....	$f_j(a_1)$	.....	.....	$f_n(a_1)$
a_2	$f_1(a_2)$	$f_2(a_2)$	.....	.....	$f_j(a_2)$	.....	.....	$f_n(a_2)$
..	.....	.....	.....	.....	.....	.....	.....	.....
..	.....	.....	.....	.....	.....	.....	.....	.....
a_i	$f_1(a_i)$	$f_2(a_i)$	.....	.....	$f_j(a_i)$	.....	.....	$f_n(a_i)$
..	.....	.....	.....	.....	.....	.....	.....	.....
..	.....	.....	.....	.....	.....	.....	.....	.....
a_m	$f_1(a_m)$	$f_2(a_m)$	.....	.....	$f_j(a_m)$	.....	.....	$f_n(a_m)$

The problem could have a third dimension if it involves multiple DMs and/or uncertainties in the PM evaluations (Mareschal 1986). At a most fundamental level, uncertainty relates to a state of the human mind, i.e. lack of complete knowledge about something. Stewart (2005) broadly categorizes the uncertainties into two groups; '*internal uncertainty'* related to the process of problem structuring and analysis, and '*external uncertainty'* regarding the nature of the environment and thereby the consequences of a particular course of action which may be outside the control of the DM. For example, decision problems related to water resources could have internal uncertainties such as the specification of preference information (e.g. importance weights and preference thresholds) and external uncertainties such as the variations in streamflow and demand patterns. In addition, another source of uncertainty associated with data errors (input errors) may be present in certain problems.

Stewart (2005) also reports that under many circumstances, the internal uncertainties can be handled by better structuring of the problem and/or by appropriate sensitivity and robustness analysis, but the external uncertainties are best handled by responses of a technical nature such as forecasting.

Among the DMCDA methods that consider the DM preferences, multi-attribute utility based methods and outranking methods have demonstrated their diversity through a vast range of applications. In a previous attempt to develop a DSS to derive optimum operating rules for Melbourne water supply system, the utility-methods were used in the MCDA (Perera et al. 1999). However, there are several drawbacks to this methodology; in particular the difficulty in constructing utility function for a single identified 'decision maker' which incorporate a DM's tradeoffs between competing system attributes and also their attitudes towards risk (Hashimoto et al. 1982). Adaptability of this utility function to sufficiently reflect the priorities of other interested groups is also doubtful (Loucks et al. 1981).

It is clear that almost all MCDA approaches use the DM preferences to make recommendations. The major difficulty facing an MCDA methodology, as many authors have highlighted (e.g. Figueira and Roy 2002; Siskos 1982), lies in the assessment and modeling of DM preferences. Logical rules and relations as well as emotional and psychological aspects of the DM are helpful in modeling DM preferences. Clearly, this will in turn have a significant impact on the outcome of the analysis. A detail discussion of preference elicitation and modeling for the case study is given in Chapter 4.

2.4.1 Additive Utility-based Methods

A major advance in decision theory came when Neumann and Morgenstern (1944) developed a formal justification for the decision analysis methods based on the expected utility. They showed that, if an individual's preferences satisfied certain basic axioms of rational behaviour, then the person's decisions could be described as the maximisation of the expected utility.

Slovic (1981) states that the additive utility-based methods were originated in 1738 when Bernoulii defined the notion of a "best bet" as one that maximises "expected utility" of the decision. That is, it maximises the quantity

$$EU(A) = \sum_{i=1}^{n} \mathrm{P}(E_i)\, U(\mathrm{X}_i)$$

Where:

$EU(A)$ - expected utility of a course of action (an alternative) 'A', which has consequences (or PM evaluations) $X_1, X_2, \ldots\ldots, X_n$ depending on events $E_1, E_2, \ldots\ldots, E_n$ and

$\mathrm{P}(E_i)$ - probability of occurrence for event E_i

$U(\mathrm{X}_i)$ - utility of the outcome X_i

One common feature in the additive utility-based methods is that they estimate and fit additive utility functions and probabilities to the PMs (Keeny and Raiffa 1976). Usually, the additive utility functions are progressively generated, using the DM's responses to making choices between alternatives. After generating these additive utility functions for all the PMs involved, the DMs can explore any number of alternatives presented to him/her and make a decision.

As reported by Pomerol and Barba-Romero (2000), there are twenty four different methods for interactive construction of the DM's additive utility function listed by Fishburn (1967). Pomerol and Barba-Romero (2000) also explain the following methods in detail:

(1) Solvability method, and
(2) Equidistant point method

The solvability method constructs the utility functions with the information gathered on the combined utilities of PMs. They also make a strong remark on the solvability method where it becomes very difficult and complex to operate when there are three or more PMs. In contrast, from a practical point of view they recommend the equidistant method, which can be easily generalised since it constructs each utility function separately.

A utility function derived using equidistant point method is shown in Figure 2.3. The equidistant point method is illustrated with the following steps to construct the additive utility functions, U_1 and U_2 and weights, w_1 and w_2 for a problem containing two PMs (Pomerol and Barba-Romero 2000):

Step 1: Determine the worst value x_0 and the best value x_1 relative to the first PM. Write $U_1(x_1) = 1$ and $U_1(x_0) = 0$.

Step 2: Ask the DM for the point equidistant in preference between x_0 and x_1; call this $x_{0.5}$ and let $U_1(x_{0.5}) = 0.5$.

Step 3: Ask the DM for the point equidistant with between x_0 and $x_{0.5}$; call this $x_{0.25}$ and let $U_1(x_{0.25}) = 0.25$. Repeat the same for $x_{0.5}$ and x_1 to obtain $x_{0.75}$.

Step 4: Verify with the DM, that $x_{0.5}$ is the point equidistant between $x_{0.25}$ and $x_{0.75.}$ This allows the consistency of the DM's replies to be checked.

Next steps: When a sufficient number of points have been found by this method, plot the function U_1 by interpolation from these points. Repeat the same procedure for U_2.

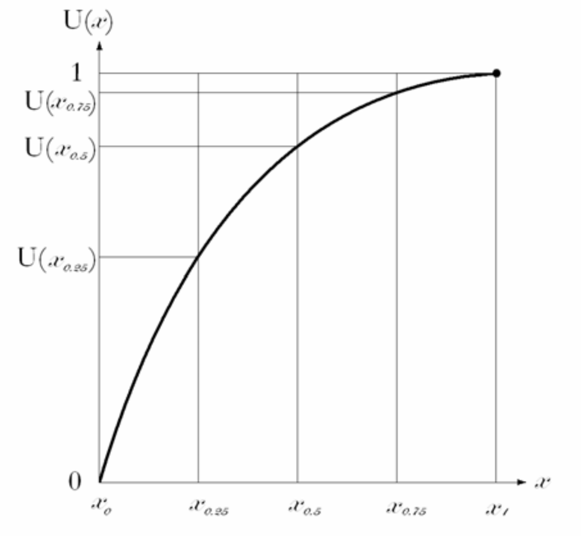

Figure 2.3: Utility Function Derived with Equidistant Point Method

Determining the weights, w_1 and w_2:

If two indifferent points on the global value function are (x_1, y_1) and (x_2, y_2), then $w_1 U_1(x_1) + w_2 U_2(y_1) = w_1 U_1(x_2) + w_2 U_2(y_2)$. As the values $U_1(x_1)$, $U_2(y_1)$, $U_1(x_2)$ and $U_2(y_2)$ are known, this enables w_1 and w_2 to be determined by the above equation in conjunction with equation $w_1 + w_2 = 1$.

One major advantage of the utility-based methods is that they could be adapted for probabilistic outcomes (Zoints 1990). However, as detailed above, the process of deriving utility functions is considered to be long and tedious, and the questions that must be addressed to the DM are not always easy to understand, which could lead to inconsistent responses. Nevertheless, for complete ranking of the alternatives, the utility-based methods provide reliable results, though it is comparatively difficult to implement than the outranking methods (Pomerol and Barba-Romero 2000).

Brans (2002) points out that in additive utility methods, though the rationality of the solution is safe, from a practical point of view, this procedure is highly questionable due the compensation effects among strong and weak criteria within the global value function. He also states that these methods impose an optimal solution to the DM, without leaving him/her any freedom for taking into account the subjectivity, emotionality and the real-life experience of the DM.

A brief overview of each of the four popular additive utility-based MCDA methods is given below.

(1) Multi-Attribute Utility Theory - MAUT (Keeny and Raiffa 1976)
(2) Analytic Hierarchy Process - AHP (Saaty 1980)
(3) Simple Multi-Attribute Rating Technique - SMART (Von Winterfeldt and Edwards 1986)
(4) Utility Theory Additive - UTA (Jacquet-Lagréze and Siskos 1982)

Multi-Attribute Utility Theory - MAUT (Keeny and Raiffa 1976)

In MAUT, the aggregation of the values is obtained by assessing partial utility functions on each PM to establish a global utility function related to a decision. Vincke

(1992) claims that MAUT was developed mostly to deal with uncertainty, and it abundantly uses the probabilities to represent some lack of precision and uncertainty which can appear in a decision problem. The two types of problems that are studied in the frame of MAUT are listed as (1992):

1. What properties must the DM's preferences fulfil in order to be able to represent them by a global utility function *U*, with a given analytical form (additive, multiplicative, mixed etc.), and
2. How such functions can be built and how can the parameters pertaining to the chosen analytical form be estimated.

This method, which has among other advantages the ability to be adapted to choice in the face of uncertainty**,** is very widely used, especially in the United States of America (Gregory and Wellman 2001; Miyamoto 1988; Prato 2003). One major shortcoming of the MAUT approach is that, in order to build the utility functions, it places very high demands on a DM, in terms of the number of judgements and their complexity (Zelany 1982).

Analytic Hierarchy Process - AHP (Saaty 1980)

The AHP method supports a strong theoretical interpretation based on the theory of graphs (Harker and Vargas 1987) and a hierarchical model is a central part of this methodology. According to Pomerol and Barba-Romero (2000), it facilitates the setting up of a hierarchy of criteria when structuring the problem and enables one of the major difficulties of MCDA, i.e. weight evaluation, to be tackled effectively.

The method arrives at the PM weights through a hierarchy so that what is finally produced is a multi-level weighted sum. The method also accepts a certain degree of inconsistency by defining an inconsistency co-efficient and involves a pair-wise comparison of alternatives for each PM. Preferential intensities are modelled by marginal value functions (Guitouni and Martel 1998). The complete method is available in the user-friendly software package EXPERT CHOICE, which is powerful and flexible.

According to Pomerol and Barba-Romero (2000), some shortcomings and limitations of this method are that:

- it forces the user to adapt to a hierarchy structuring,
- the final ranking of a previously analysed set of alternatives can be perturbed by introducing new alternatives,
- it requires a lot of information from the DM, in order to construct the utility functions, and
- utility normalization problems.

However, AHP has been successfully used in a wide range of applications from corporate planning (strategy planing, choice of projects, choice of investments, choice of equipment, commercial prospecting, auditing etc.) to the resolution of international conflicts (Zelany 1982).

Simple Multi-Attribute Rating Technique (SMART) - (Von Winterfeldt and Edwards 1986)

SMART models the preference intensities for the alternatives by a marginal value function on the set of alternatives (similar to the AHP method), for each criterion separately (Von Winterfeldt and Edwards 1986). This is a simple way to implement the MAUT by using the weighted linear averages, which gives extremely close approximations to utility functions. There are many improvements to this method like SMARTS and SMARTER (Edwards and Barron 1986).

The shortcomings of the method include the dependency upon the cardinality and the normalization of the alternatives (Pomerol and Barba-Romero 2000).

Utility Theory Additive (UTA) - (Jacquet-Lagréze and Siskos 1982)

The UTA method employs a computerized mathematical procedure to evaluate the utility functions associated with each PM within a context of global comparisons that the decision maker makes in a sub-set of alternatives, called the *reference set*; the term global meaning that '*each alternative is considered as a whole and there is no separation- even mental- between criteria*' (Jacquet-Lagréze and Siskos 1982).

Once the utility functions of each PM have been established, a DM's additive utility function (enabling all the alternatives in the choice set to be evaluated) is constructed. The parameters of these functions are determined to be consistent with the previously stated preferences (usually called ordinal regression). Then the global value function is obtained in an additive manner leading finally to solve a linear program. The method assumes that the preferences in the reference set are to be transitive (to agree with each other) and declare this assumption for achieving minimum consistency of the results. The quality of the results, which depends on the size of the reference set is also considered to be a shortcoming of the method. In general, UTA gives fairly reliable information with a good well-classified reference set, and it does not require a large amount of information from the DM (Pomerol and Barba-Romero 2000).

There are two commercially available software packages that employ the UTA method, i.e. UTA PLUS (originally appeared as PREFCALC) and MINORA (Hadzinakos et al. 1991). The details of UTA PLUS software package are given in Section 2.5.

2.4.1.1 General Applications

Tzeng et al. (1992) describes an MCDA model which aids the Taipei city administration in planning its budget allocation among eighteen items, identified as PMs, concerning the living environment. The model, which had five main objectives, employed the AHP method to estimate the weights of PMs, the additive utility functions for estimating preferences and the compromise programming sub model for optimising an investment plan under governmental budgets and civic satisfaction constraints.

To integrate the environmental concerns at an early stage of planning, Kim et al. (1998) applied the multi-attribute utility theory (MAUT) to obtain the value judgments on the significance of environmental impacts of an electric utility in Korea. An environmental multi-attribute index is constructed as a multi-attribute utility function, based on value judgments provided by a group of experts related to electric utility and a decision maker from Korea Electric Power Corporation (KEPCO). The societal values are derived from examining trade-offs between the environmental index and the financial considerations. The study concluded that results can provide valuable insights and decision opportunities for major decision making in environmental planning facing KEPCO.

Herath (2004) employed AHP method to evaluate planning and management options of the ‘Wonga Wetlands’ on the Murray River in Australia. The study illustrates how the stakeholder preferences on the multiple objectives related to ecological, economic, environmental and social aspects can be incorporated into the decision analysis of the alternatives. The study concludes that the success of the AHP method depends on the way the decision problem is structured, how the pair-wise comparisons are carried out, and the ability of respondents in providing credible answers to the questions posed.

2.4.1.2 Water Resources Applications

In the field of water resources planning, Jabor and Mohsen (2001) used AHP to evaluate non-conventional water supply sources in Jordan. The four alternative supply sources viz. (1) using treated wastewater, (2) rainwater harvesting, (3) importing water, and (4) desalination of brackish water were evaluated under five PMs related to technical, availability, environmental, reliability and economical aspects of the problem.

Joubert et al. (2003) employed MAUT and additive utility functions to evaluate and sort water supply augmentation and water demand management options for the City of Cape Town in South Africa where the water demand was rapidly reaching the yield and also severe water restrictions had to be imposed in summer 2000-2001 to regulate the demand. Fourteen alternatives, i.e. 4 supply augmentation alternatives, 6 demand control alternatives and 4 water reuse alternatives were evaluated using nineteen PMs under five main objectives. These evaluations assisted in constructing a consensus set of recommendations among external consultants working together with technical experts and council officers.

Duckstein et al. (1994) applied additive utility functions and UTA methods together with ELECTE III and Compromise Programming (a distance-based method) to rank thirteen groundwater management alternatives. Three objectives that were considered in the study are:

1. Maximisation of total pumping rates over the aquifer,
2. Minimisation of operating costs including water pumping and transportation, and
3. Minimisation of risk interpreted as the percentage uncertainty in water quantity at the exploitation stage.

2.4.2 Outranking Methods

Emerged during the sixties through the influence of French workers, the outranking methods have been proposed for aggregating preference information on several PMs into an overall preference structure in cases where the multi-attribute utility approach is not appropriate or feasible. Vincke (1992) states that the underlying idea of introducing the outranking methods is that it is better to accept a result less richer than that yielded by MAUT, if one can avoid mathematical hypotheses which are too strong and requiring complex information from the DM.

Initially, the lack of theoretical foundation for outranking procedures is probably one of the reasons why these methods were not fully recognized at least among theoreticians of MCDA although the first papers about ELECTRE, one of the first outranking methods to appear in literature, dated back to the late 1960s (Perlot 1997; Vincke 1992). In exploring ways to provide formal foundations to known outranking methods, Perlot (1997) suggested a common framework to describe them. However, the theoretical framework of outranking methods has changed by the nineties (Roy 1990), demonstrating its diversity through a vast range of applications and giving them a stronger foundation (Pomerol and Barba-Romero 2000).

The theory of non-compensatory preference structures also served as a starting point for one of the few attempts to establish outranking methods on theoretical grounds (Fishburn 1976). These methods offer more freedom to the DM to express his/her preferences on performance measures in a structured manner and are based on a pair-wise comparison of alternatives to aggregate the DM's preferences.

Problems of selecting one or few satisfactory alternatives are best handled by the outranking methods because of their ability to fine tune the DMs' preferences and comparatively low information requirement from the DM (Pomerol and Barba-Romero 2000). The outranking methods have seen a rapid development during last few decades because of their adaptability to the poor structure of most real decision situations. Over the past three decades, the outranking methods have been widely applied for major engineering related projects (Georgopoulou et al. 1998; Rogers and Bruen 1997; Spengler et al. 1998).

Perlot (1997) states that the outranking methods are also uniquely characterized by the limited degree to which a disadvantage on a particular viewpoint may be compensated by advantages on other viewpoints (i.e. non-compensatory nature). This means that in comparing two alternatives, 'small' differences in favour of one of them may be compensated by the 'small' differences in favour of the other one, but 'large' differences may not be compensated even by 'large' differences in the opposite direction. Such a feature yields overall preferences in which some pairs are incomparable.

Outranking Concept

In general terms, Roy (1968) defines an outranking relation of two alternatives *a* and *b*, as a binary relation *S* defined on a set of alternatives *A*, such that *a* S *b* if,

- given what is known about the DM's preferences, and
- given the evaluations on alternatives and the nature of the problem,

there are enough arguments to decide that *a* is at least as good as *b*, while there is no essential reason to disapprove that statement.

While the above outranking concept is not a precise mathematical definition but rather a general idea, Vinke (1992) argues that it is not necessary for an outranking relation to be complete or transitive, but it could well define a partial pre-order (or ranking).

The concept of pseudo-criterion (PMs with preference thresholds) is also used in some outranking methods to express the DMs' preferences on PMs in the most general way. For each PM, an indifference threshold, *q*, and a preference threshold, *p*, should be defined ($p > q$). These thresholds are used to compare the evaluations of the alternatives *a* and *b,* relative to that PM. Most of these methods also involve a notion of 'weights' for the PMs, representing their relative importance.

Outranking methods comprise two steps:

Step 1: Building the outranking relationship, and

Step 2: Exploiting the relationship in relation to the chosen statement of the problem

The outranking methods, which have been proposed in the literature, differ, among other aspects, by the way that each method formalises the above concepts. ELimination Et Choix Traduisant la REalite' (ELECTRE) - (Roy 1968), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) - (Brans et al. 1986), Organization, Rangement Et Synthese de dones relaTionnElles (ORESTE) - (Roubens 1982), Tratement des Actions Compte Tenu de l'Importance des Crite'res (TACTIC) - (Vansnick 1986), EVAMIX (Voogd 1983), REGIME (Hinloopen et al. 1983), and Multicriterion Analysis of Preferences by means of Pairwise Alternatives and Criterion comparisons (MAPPAC) - (Matarazzo 1986) are among the popular outranking methods suggested in literature. A detailed explanation of the outranking concept as used in PROMETHEE method is given in Section 2.7.2, since PROMETHEE is employed for decision analysis in this study.

ELECTRE and **PROMETHEE** are two most widely used outranking methods that allow interactive learning. They stimulate to exploration through their facilities for sensitivity analysis due to the interactive fixing of the various decision parameters. These methods are based on a pair-wise comparison of alternatives (for each criterion separately) and aggregating the DM preferences on each PM, instead of building, for each alternative, a numerical evaluation on a common scale such as in MAUT. However, in some cases, the pair-wise comparison could cause the overall preference to be intransitive.

The general and water resources specific applications, which use ELECTRE and PROMETHEE methods, are given in Sections 2.4.2.1 and 2.4.2.2 respectively, and a brief overview of ELECTRE and PROMETHEE methods are given below.

ELimination Et Choix Traduisant la REalite'(ELECTRE) Methods - (Roy 1968)

The ELECTRE methods engage the outranking concept with the notions of 'concordance' and 'discordance'. When an alternative *a* is at least as good as an alternative *b* for a majority of criteria (concordance principle), and there exists no criterion for which *a* is substantially less good than *b* (non-discordance), it is safe to conclude that *a* outranks *b*.

Since the introduction of the original version ELECTRE I (Roy 1968), the other versions ELECTRE II (Roy and Bertier 1973), ELECTRE III (Roy 1978), ELECTRE IV (Roy and Hugonnard 1982), ELECTRE IS (Roy 1985) and ELECTRE TRI (Mousseau et al. 1997) have emerged. ELECTRE I, ELECTRE IS and ELECTRE TRI yield a global outranking relation defined over the alternatives, which is represented by an oriented value graph. From this graph, the information required to make a selection can be extracted. This global outranking relation is strongly influenced by the preference thresholds defined by the DM. Contrarily, ELECTRE II, ELECTRE III and ELECTRE IV lead directly to a ranking of all the alternatives, based on the aggregated preferences for each alternative. ELECTRE TRI deals with the problem of sorting the alternatives into pre-defined sub-groups (the classification problem). ELECTRE IV is the only ELECTRE type method which do not require PM weights, but operates through a set of outranking relations, embedded in each other, which are constructed progressively (Pomerol and Barba-Romero 2000).

One unique feature in ELECTRE methods is that they allow the introduction of the notion of veto in the PMs (Roy 1990). Veto threshold characterises the situation where a discordant PM can, on its own, exert a veto on an entire outranking relationship. It must at least be set equal to the preference threshold (*p)*, and is usually set at three times the preference threshold (*p*) (Rogers et al. 2000b). By giving a PM the opportunity to veto, modifies that PM's role (importance) as compared to the other PMs. Veto criterion coefficients are intra-criteria parameters like *p* and *q* threshold values. The veto threshold is defined as the smallest difference, between the performances of the two alternatives, above which the DM thinks it is not possible to support the idea that the worse of the two alternatives (under consideration on this PM) may be comprehensively considered as the better one even if its performances on all the other PMs are better. In ELECTRE methods, it is possible to give the opportunity to veto to one, several or all PMs.

Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) Method - (Brans et al. 1986)

This is one of the most recent outranking methods, which has been used more and more frequently. The main feature claimed for this method is that it is perfectly intelligible for the decision maker and it is indeed one of the most intuitive of multi-criterion methods (Pomerol and Barba-Romero 2000). The method introduces six preference function (generalized criteria) types to describe the DM preferences. For each PM, it requires a weight and a criteria type to be specified by the DM.

PROMETHEE I ranking is based on the same principles as ELECTRE type methods. This procedure provides a partial ranking of the alternatives (i.e. it focuses on the best alternative, not on a complete ranking) based on preference aggregation. Pairs of alternatives are categorized by preference (**P**), indifference (**I**) or incomparability (**R**). PROMETHEE II is based on the same principles as PROMETHEE I, but provides a total preorder of the alternatives using preference aggregation.

In contrast to ELECTRE methods, PROMETHEE introduces the thresholds in the preparatory phase of criterion definition. A certain amount of subjectivity is involved especially in setting thresholds of the pseudo-criteria (i.e. PMs with preference thresholds), rather similar to what happens in ELECTRE methods, with concordance and discordance thresholds; however, according to Brans *et al.* (1986), PROMETHEE has the advantage over ELECTRE of robust results able to survive threshold modifications. More details of the PROMETHEE method are given in Section 2.7.1.

2.4.2.1 General Applications - ELECTRE and PROMETHEE

Rhodes et al. (2005) used PROMETHEE outranking approach to evaluate a range of alternative koala habitat protection strategies for a population in New South Wales, Australia. The study focussed on an overall goal of minimising the risk of koala population decline, with four alternative habitat protection strategies. They conclude that in natural resource management, where uncertainty is central to robust decision-making, the outranking approach could provide a straightforward and transparent means of incorporating parameter uncertainty in the decision analysis.

Martel and Thomassin (1990) employed the ELECTRE II method to rank 48 surgical operations according to their priority, taking into account the available resources, the surgeons preferences, the medical requirements of every patient and several characteristics of each operation. They claim that ELECTRE II, which has been developed to deal with ranking of alternatives, is a simple and easy to apply method.

Rogers et al. (2000a) employed the ELECTRE III methodology in a group decision making setting to analyse eleven strategic alternatives and to decide on the optimum waste incineration strategy for the eastern Switzerland region in future. The study used eleven PMs with four objectives covering environmental, economic, technical, and political aspects of the problem to evaluate and analyse the alternative strategies. The decision-making group comprised eight members representing various organizations with voting powers given only to six members.

2.4.2.2 Water Resources Applications - ELECTRE and PROMETHEE

In the context of water resources planning, among many other applications (Duckstein et al. 1994), the ELECTRE method has been used to analyse alternative planning policies for the Flumen Monegros irrigation system in Spain (Srinivasa Raju et al. 2000), to examine the impacts of alternative river basin development strategies for Santa Cruz River Basin in Tucson, Arizona, USA (Gershon et al. 1982) and to choose the optimum river basin planning strategy for the reservoirs in Krishna River Basin in South India (Anand Raj 1995).

Srinivasa Raju et al. (2000) used a total of ten PMs considered under economic, environmental and social aspects as follows:

1. Economic factors (4 PMs); initial cost of the irrigation system, maintenance cost, profitability of crops and extent of European subsidies.
2. Environmental factors (4 PMs); irrigation water volume, water quality after irrigation, efficiency of water use and resistance to floods or droughts.
3. Social factors (2 PMs); employment of rural labour and area non-cultivated.

Alternative planning policies were formulated by mixing factors such as irrigation system, water pricing, water allocation, crop distribution, fertiliser use and subsidies received. Multi-criteria sorting technique, ELECTRE-TRI was first employed to reduce the large size decision matrix to pre-defined categories. Then five MCDA techniques, namely, PROMETHEE II, EXPROM-2 [a combination of outranking and distance-based methods (Raju and Duckstein 2000)], ELCTRE III, ELECTRE IV and Compromise Programming were applied to analyse and rank the alternatives. In conclusion they stated that:

- ELECTRE TRI was a useful screening methodology when the number of alternatives and/or PMs was large,
- All the five MCDA techniques found the same best planning strategy, and
- EXPORM-2 and Compromise Programming yielded the same ranking pattern.

Gershon et al. (1982) applied ELECTRE I and ELECTRE II to examine the twenty-five alternative river basin development strategies for Santa Cruz River Basin. The process started with definition of system objectives. There were five objectives considered in the study and these objectives were related to: (1) water supply, (2) flood protection, (3) environmental, (4) utilisation of resources, and (5) recreation. Thirteen PMs were used to evaluate the performance of each alternative strategy.

In a similar study, Anand Raj (1995) also applied ELECTRE I and ELECTRE II to evaluate twenty-seven alternative river basin planning strategies for the Krishna river basin consisting of eight reservoirs and one diversion work. The alternatives considered were the different combinations of reservoir planning policies with a minimum of three reservoirs in each alternative. These alternative planning strategies were evaluated with the aid of six PMs, namely, irrigation, power production, drinking water, environmental quality, floods and cost of the project.

Both Anand Raj (1995) and Gershon et al. (1982) obtained a set of best alternative strategies with the partial ranking given by ELECTRE I, which formed the input for ELECTRE II. They recommended ELECTRE I for screening the alternatives to narrow the set of alternatives under consideration and ELECTRE II for complete ranking of the reduced set.

2.5 Software for Discrete Multi-Criteria Decision Aiding

Vincke (1992) points out that it is impossible to give a complete inventory of all the MCDA software programs for at least two reasons mentioned below:

1. In addition to the commercially available software, there are many high quality computer programs developed in academic/research organizations, which only researchers are able to access, and
2. The rapidity of the development of this area of study, which makes any attempt to comment or compare the software irrelevant.

Despite above reasons, in the recent past, several researchers have attempted to evaluate the available MCDA software. They include Pomerol and Barba-Romero (2000), Weistroffer et al. (2005), Anderson (2002), French and Xu (2005), and Geldermann and Zhang (2001). Weistroffer et al. (2005) report that the early systems of MCDA programs were implemented on mainframe computers with no documentation available, and they also lacked any visual representation capabilities, mainly due to the limited knowledge and access to the computer technology at that time.

In 1970s, MCDA software programs were primarily developed for academic purposes and mainly oriented towards the study of multiple objective mathematical programming problems (Dyer 1973). However, during the 1980s, the emphasis shifted away from the mathematical aspects of multiple objective programming towards providing decision support to the DM (Korhonen et al. 1992). Most modern MCDA software tools are designed for the Windows platform and provide graphical interfaces to assist in visualising the effects of changes to problem parameters (Weistroffer et al. 2005).

Currently, there is a wide variety of software that has been developed by academics and software companies specifically to support DMCDA. However, according to Pomerol and Barba-Romero (2000) not all of these software can be considered as ‘alive’ since some of them may now have been abandoned, become obsolete or hard to find. While most software developed by academics are available free of charge, or for a nominal fee, commercial packages sell for hundreds or thousands of dollars (Weistroffer et al. 2005). Most of the software also has their own websites where demonstration versions could be downloaded.

As reported by Pomerol and Barba-Romero (2000), Weistroffer et al. (2005), Anderson (2002), Linkov et al. (2006) and relevant web pages, the details of the following seventeen DMCDA software packages are given in Appendix A.

The descriptions, limitations and applications of these software packages are presented in Table A-1 (Appendix A), while the special features and information sources are given in Table A-2 (Appendix A).

AIM (**A**spiration-level **I**nteractive **M**odel): (Lofti and Zoints 1990)

CRITERIUM DECISION PLUS: (Saaty 1995)

DECISION LAB 2000 (improved PROMCALC): (Visual Decision 2003)

DEFINITE: (Herwijnen and Janssen 1989)

ELECCALC: (Kiss et al. 1992)

ELECTRE 1S: (Roy 1968; Roy 1978)

ELECTRE III-IV: (Roy 1978; Roy 1990)

EXPERT CHOICE: (Saaty 1995)

HIPRE3+ (**HI**erarchical **PRE**ferences): (Wesseling and Gabor 1994)

HIVIEW and EQUITY: (Philips 1990)

LDW (**L**ogical **D**ecision for **W**indows): www.logicaldecisions.com

MACBETH (**M**easuring **A**ttractiveness by a **C**ategorical **B**ased **E**valuation
Tec**HN**ique): (Bana e Costa and Vansnick 1997; 1998)

QUALIFLEX (**QUALI**tative and **FLEX**ible assessments): (Linden and Stijnen 1995)

UTA PLUS (improved PREFCALC)**:** (Jacquet-Lagreze 1990)

VIMDA (Visual Interactive Method for Discrete Alternatives):
(Korhonen and Laakso 1986)

V.I.S.A. (Visual Interactive Sensitivity Analysis): (Belton and Vickers 1990)

While some software packages are specific to only one MCDA methodology, others provide the facility for the DM to choose among many methodologies. Table 2.2 shows the different MCDA methodologies promoted in each of the above software packages.

Table 2.2: Discrete Multi-Criteria Decision Aiding (DMCDA) Methods Associated with Various DMCDA Software Packages

Software package		Ordinal Methods		Utility methods				Outranking Methods												Other methods
	Weighted sum	Borda's method	Condorcet's method	MAUT	AHP	SMART	UTA	ELECRE I	ELECRE II	ELECRE III	ELECRE IV	ELECRE IS	PROMETHEE I	PROMETHEE II	ORESTE	TACTIC	REGIME	MAPPAC	EVAMIX	
AIM								x												Distance-based method
CRITERIUM DECISION PLUS					x	x														
DECISION LAB 2000													x	x						
DEFINITE	x								x								x		x	
ELECCALC									x											
ELECTRE 1S								x				x								
ELECRTE 111-1V										x	x									
EXPERT CHOICE					x															
HIPRE3+					x															
HIVIEW & EQUITY	x																			
LDW				x	x	x														
MACBETH				x																
QUALIFLEX																				Permutation methods (Linden and Stijnen 1995)
UTA PLUS							x													
VIMDA																				Interactive comparison of alternatives (Korhonen and Laakso 1986)
VISA	x																			

2.6 Decision Support Systems with MCDA

Computer-based models together with their interactive interfaces are typically called decision support systems (DSSs). Loucks (1995) states that the common objective of all DSSs, regardless of the frameworks, methodologies or techniques used, is to provide timely information that supports human decision makers - at whatever level of decision making. He also reports that in spite of the growth of DSS development and substantial use, the computer-aided DSSs can still be improved and made more useful to those they are intended to support. There are numerous general applications of DSSs with MCDA reported in literature.

Spengler et al. (1998) developed a MCDA based DSS named KOSIMEUS for environmental assessment of recycling measures in the iron and steel industry. KOSIMEUS, which is a combination of process models simulated with a flow-sheeting program and PROMETHEE outranking approach was applied to a case study to select the best alternative for the recycling of dusts and sludges resulting from a tinplate production process. They also claim that the PROMETHEE outranking approach has proved to be an easy to use evaluation method, which brings in flexibility and simplicity together for the user.

Georgopoulou et al. (1998) presented a Group DSS designed for supporting computational tasks and facilitating decision analysis in energy planning. They employed the PROMETHEE outranking approach in the MCDA module. The DSS was applied in a real decision situation concerning the formulation of an operational plan for Renewable Energy Source (RES) exploitation in Greece. Eight RES penetration scenarios were evaluated with the aid of eight PMs and a DMG comprising twelve DMs representing government authorities, industrial association and non-governmental organizations.

Some MCDA based DDS applications have also been reported in water resources management for conflict resolution (Rajasekaram and Nandalal 2005), river basin flood control (Shim et al. 2002) and reservoir operation (Westphal et al. 2003).

Rajasekaram and Nandalal (2005) developed a DSS for reservoir water management conflict resolution (RWM-CRSS) for a multi-purpose single reservoir. The system consisted of a communication system, a database management system, and a model-based management system. RWM-CRSS was designed to handle conflict between two groups who have on-demand water requirements for irrigation, drinking water, hydropower generation, or minimising flood damage.

Shim et al. (2002) demonstrated a prototype Spatial Decision Support System (SDSS) for integrated, real-time river basin flood control in a multi-purpose, multi-reservoir system. This SDSS integrated a geographic information system with a database management sub-system, a real-time meteorological and hydrological data monitoring system, a model-based sub system for system simulation and optimisation, and a graphical dialog interface allowing effective use by system operators. The SDSS for flood control is applied to the Han River basin in Korea and demonstrated through simulated application to a severe flood event in 1995. The results on the case study suggested that integrated operational strategies generated by this SDSS for flood control substantially reduced downstream flood impacts, while maintaining sufficient storage subsequent to the flood season.

Westphal et al. (2003) developed a real-time DSS for adaptive management of the reservoir system that provided drinking water to Boston metropolitan region in USA. The DSS uses a systems framework to link watershed models, reservoir hydraulic models, and a reservoir water quality model. The DSS offers the ability to optimise daily and weekly reservoir operations towards four objectives based on short-term climate forcasts: (1) maximum water quality, (2) ideal flood control levels, (3) optimum reservoir balancing, and (4) maximum hydropower revenues. They highlighted the value of the DSS as an enhancement to the current rule curve operations.

In a previous attempt to derive optimum operating rules for the Melbourne water supply system, REALM (Perera and James 2003; Perera et al. 2005) water supply simulation software and LDW multi-criteria decision analysis software (Logical Decisions 1997) were used in a DSS (Perera et al. 1999). The Melbourne water supply system REALM model was used as a simulation model to assess the system PMs under alternative operating rules and then the performance of these operating rules were analysed using the LDW software. Once the DMs' preferences in terms of weights and utility functions were defined for all PMs, the DSS was able to provide a complete ranking of the alternative operating rules. However, inheriting from the utility-based methods, this DSS had the drawback of demanding considerable amount of information from the DMs in order to construct the utility functions. The current study described in this thesis was undertaken to strengthen the decision analysis module to derive the optimum operating rules for urban water supply systems in a generic decision support framework proposed by the previous study of Perera et al. (1999).

2.7 Selection of an MCDA Technique and Software for the Study

Available MCDA methods so far differ with each other in the quality and quantity of additional information they request, the methodology they use, their user-friendliness, the sensitivity tools they offer, and the mathematical properties they verify. Many authors have recognized that **ease of use** and **understandability** by the DM are important factors in the DM accepting the method (Buchanan and Daellenbach 1987; Olson et al. 1998; Srinivasa Raju and Pillai 1999; Wallenius 1975). As described in Section 2.5, there are numerous DMCDA software packages, which have attained a high professional degree of development. The features such as commercial availability, applicable to many real problems, representativeness of their methodology and wide use could be some governing guidelines in selecting the appropriate software for the intended purpose (Pomerol and Barba-Romero 2000).

Guitouni and Martel (1998) report that despite the development of a large number of refined MCDA methods, none can be considered as the 'super method' appropriate to all decision-making situations. They also present tentative guidelines to help choosing an appropriate MCDA method with a comparative study of some discrete MCDA approaches.

Salminen et al. (1998) compared three MCDA methods ELECTRE III, PROMETHEE and SMART in the context of four different real applications in environmental decision-making. They stated that the choice of a certain method could be decided in the beginning of the process, but it has to wait until the analysts and DMs understand the problem; the feasible alternatives, different outcomes, conflicts between the PMs and the level of uncertainty of the data. They also concluded that the choice in practice may not be easy due to the fact that, the results (rankings of alternatives) did not differ much from each other. However, they further stated that, in a particular problem, the 'best alternative' obtained with these methods could differ greatly.

One of the most known and widely used outranking methods, PROMETHEE with its computer software tool, *Decision Lab 2000* was chosen for this study, primarily because of its transparent computational procedure and simplicity (i.e. comparatively low time and effort required of the DM to reach a conclusion). There are numerous planning and management applications that have been analysed by PROMETHEE (e.g. Briggs et al. 1990; Georgopoulou et al. 1998; Spengler et al. 1998; Srinivasa Raju et al. 2000; Vuk et al. 1991), where they recognise the transparency and the simplicity of the method. The computational procedure of PROMETHEE is given in Section 2.7.1 and the details of *Decision Lab 2000* software are given in Section 5.3.

2.7.1 PROMETHEE Methodology

Apart from the basic data required in the form of a decision matrix (as shown in Table 2.1), PROMETHEE requires some additional preference information from the DMs. These preferences should be modelled in such a way that it provides the specific input information in the required form. The following two types of information derived for each DM facilitate preference modelling in PROMETHEE:

1. A Preference Function (PF) for each PM, and
2. Relative importance of PMs (expressed by weights)

(a) Preference Function

A preference function, *p(x)* is introduced for each PM in order to allow the comparison of different PMs independently to their measurement units and also to control the unwanted compensatory effects when aggregating the preferences. In pair-wise comparison of alternatives, the PF translates the deviation (*x*) between the evaluations of the two alternatives on a single PM, to a preference degree (i.e. preference intensity), which will have a value between 0 and 1. The PF is an increasing function of the deviation; smaller deviations will contribute to weaker degrees of preference and larger ones to stronger degrees of preference. Negligible deviations would indicate indifference in preferences (Visual Decision 2003).

To facilitate the association of a preference function to each PM, the authors of the PROMETHEE method (Brans et al. 1986) have proposed six specific shapes as shown in Figure 2.4. While they claim that these six types of PFs are satisfactory for many real world applications, there is no objection to consider any additional generalised criteria types in the PROMETHEE method (Brans and Mareschal 2005). However, PROMCALC and Decision Lab 2000 software facilitate only the six shapes given in Figure 2.4. Each shape depends on up to two thresholds; indifference threshold (*q*), preference threshold (*p*) and Gaussian threshold (*s*). Type I, Type II and Type III are variants of Type V.

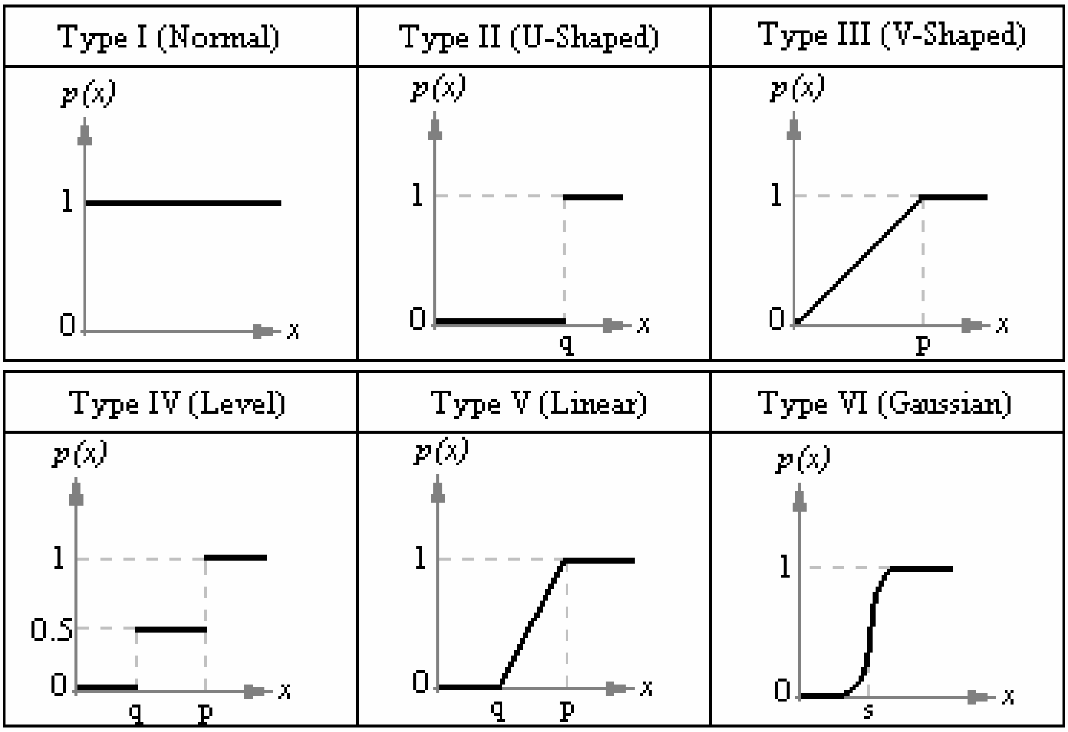

Figure 2.4: Generalized Preference Function Types of PROMETHEE
(Source: Brans and Mareschal 2005)

Each PM could have a different PF, by defining its parameters, either '*q*' and '*p*', or '*s*'. Therefore it is necessary to set these parameters to customize the preference intensity for each PM. For example, the DM sets the curve Type V with q = 10% and p = 20% for a certain PM, PM1 (assume PM1 is monthly reliability of water supply which is defined by the percentage of non-restricted months to the total months in a planning period for supplying water from a water supply system). When comparing two alternatives, this would mean that with a difference of monthly reliability of supply of less than 10%, the DM considers the alternatives are indifferent, while a difference of between 10% and 20%, DM indicates a weak preference of the higher-valued alternative. With any difference above 20%, the DM indicates a strong preference for the higher-valued alternative.

(b) Weights

Often in MCDA, a DM sees one PM is more (or less) important than another; this may be for various reasons including personal preferences which may be reasonably objective, but completely subjective (Pomerol and Barba-Romero 2000). To express these differences, what PROMETHEE requires is a set of weights (or relative importance), $\{w_{j,}, j=1,2,....n\}$ for n number of PMs which are derived for each DM, where the normalised weights would add up to 1 (i.e. $\sum_{j=1}^{n} w_j = 1$). From a DM's point of view, the higher weights would naturally be assigned for more important PMs and the lower weights would be assigned for less important PMs.

2.7.2 PROMETHEE Methodology – Single DM Case

PROMETHEE is a preference aggregation method based on pair-wise comparison of all possible combinations of alternatives (Brans and Mareschal 2005). The method, which was developed first for single DM case, comprises two steps:

STEP 1 - Construction of an outranking relation by aggregating the information about the alternatives and the criteria, and

STEP 2 - Exploitation of the outranking relation for decision-aid.

STEP 1 – Constructing the outranking relation

Consider the family of ***n*** PMs, $\{f_1(.), f_2(.) \ldots\ldots f_j(.) \ldots., f_n(.)\}$, to evaluate a finite set **A** of ***m*** possible alternatives, $\{a_1, a_2, \ldots a_i \ldots, a_m\}$. As the first step, based on the information provided by the DM, a set of importance weights, $\{w_j, j=1,2,\ldots.n\}$ as well as a set of generalized preference function types, $\{p_j(x), j=1,2,\ldots,n\}$ will be derived.

For each pair of alternatives (say *a* and *b*) in set **A**, as described in Section 2.7.1 (a) above, the preference function gives the preference for alternative *a* with regard to alternative *b,* as a function $p_j(x)$; where $x = f_j(a) - f_j(b)$, for a particular PM. The outranking relationship is then represented by a valued outranking graph as shown in Figure 2.5. This figure shows an example with 4 alternatives [a, b, c, d]. The value of each arc is the *multi-criteria preference index, π (a, b)***,** which is defined below for all ordered pairs of alternatives in set **A**.

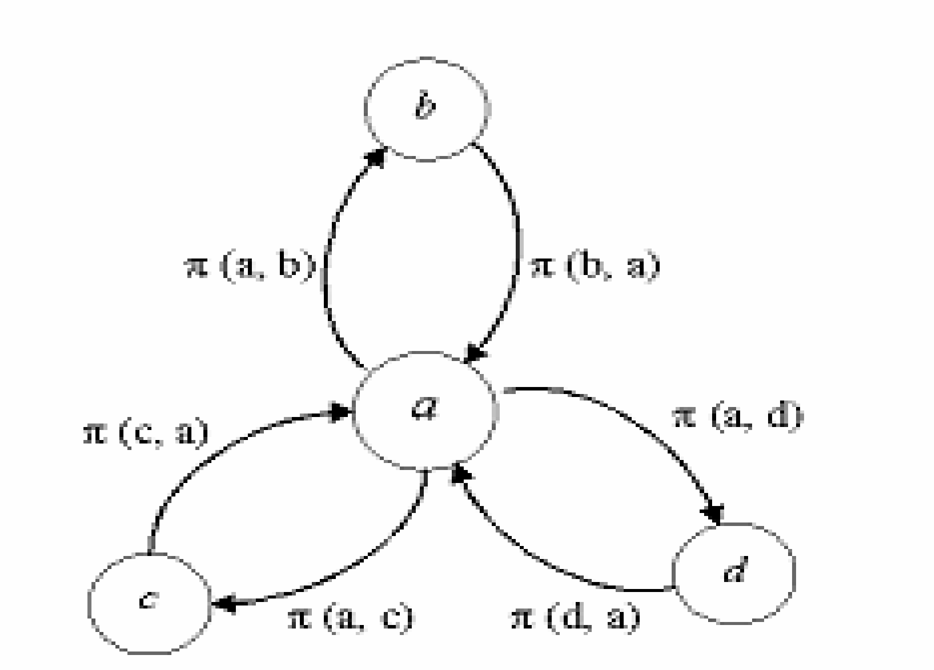

Figure 2.5: Valued Outranking Graph

In Figure 2.5, the *π* terms for alternatives a and b are defined as below, considering all PMs.

$$\pi (a, b) = \sum_{j=1}^{n} w_j p_j[f_j(a) - f_j(b)]$$

$$\boldsymbol{\pi}(b, a) = \sum_{j=1}^{n} w_j p_j [f_j(b) - f_j(a)]$$

where w_j - relative importance (or weight) of PM

The above valued outranking graph can then be exploited for decision aiding by means of PROMOTHEE rankings, as described in Step 2 below.

STEP 2 – Exploitation of outranking graph for decision-aid

Two approaches are available in PROMETHEE for exploiting the valued outranking graph, one for PROMETHEE I and the other for PROMETHEE II. Both are based on outgoing flow, $\Phi^{+}(a)$ and incoming flow, $\Phi^{-}(a)$ at each node (or alternative) in the valued outranking graph.

$\Phi^{+}(a) = 1/(m-1)\sum_{i=1}^{m} \pi(a,i)$ - defines the strength of the alternative *a* and expresses how much '*a*' is *outranking* (m-1) other alternatives

$\Phi^{-}(a) = 1/(m-1)\sum_{i=1}^{m} \pi(i,a)$ - defines the weakness of the alternative *a* and expresses how much '*a*' is *outranked* by (m-1) other alternatives

PROMETHEE I obtains a partial preorder (**P**, **I**, **R**) from two different complete preorders ($\mathbf{P}^{+}$, $\mathbf{I}^{+}$) and ($\mathbf{P}^{-}$, $\mathbf{I}^{-}$), where **P** stands for strict preference, **I** stands for indifference and **R** stands for incomparability. This partial pre-order is achieved by considering:

$a\,\mathbf{P}^{+}\,b$ iff $\Phi^{+}(a) > \Phi^{+}(b)$,
$a\,\mathbf{I}^{+}\,b$ iff $\Phi^{+}(a) = \Phi^{+}(b)$,
$a\,\mathbf{P}^{-}\,b$ iff $\Phi^{-}(a) < \Phi^{-}(b)$, and
$a\,\mathbf{I}^{-}\,b$ iff $\Phi^{-}(a) = \Phi^{-}(b)$

which gives;

$a\,\mathbf{P}\,b$ if [$a\,\mathbf{P}^{+}\,b$ and $a\,\mathbf{P}^{-}\,b$] or
if [$a\,\mathbf{P}^{+}\,b$ and $a\,\mathbf{I}^{-}\,b$] or
if [$a\,\mathbf{I}^{+}\,b$ and $a\,\mathbf{P}^{-}\,b$]

$a\,\mathbf{I}\,b$ if [$a\,\mathbf{I}^{+}\,b$ and a $\mathbf{I}^{-}\,b$]

$a\,\mathbf{R}\,b$ otherwise [i.e. If not $a\,\mathbf{P}\,b$ or $a\,\mathbf{I}\,b$]

PROMETHEE II produces a complete preorder (**P**, **I**) from net preference flow $\Phi(a)$, where, $\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$, considering,

$a \mathbf{P} b$ iff $\Phi(a) > \Phi(b)$, and
$\mathrm{a} \mathbf{I} \mathrm{b}$ iff $\Phi(\mathrm{a}) = \Phi(\mathrm{b})$

There is also a descriptive complement to the PROMETHEE methodology, GAIA (**G**raphical **A**nalysis for **I**nteractive **A**ssistance) plane, a visual interactive module based on 'Principal Components Analysis' method. Briefly, the GAIA plane gives the best possible two-dimensional representation of all the data in a problem, enabling to visualize the conflicts between PMs. This visual display is incorporated in *Decision Lab 2000* software. A detailed description of GAIA is given in Section 5.3.

2.7.3 PROMETHEE Group Decision-Making Extension

Macharis et al. (1998) developed the PROMETHEE GDSS (Group Decision Support System), which extends the PROMETHEE methodology into its group decision-making capabilities. It provides decision aid to a group of DMs (DM_1, DM_2,…..,DM_r, …. DM_R), who will eventually be contributing to a single decision. For the procedure to be more effective with immediate feedback from the DMs, it has been designed to use in a GDSS room with each DM in a separate working station, connected to a facilitator through a local network, or in a framework of teleconference or videoconference systems. However, in decision problems where there is a large number of DMs involved, practical difficulties could arise in arranging a meeting with all the DMs. Alternatively, in these situations, a facilitator could gather all the necessary information, analyse them, explain the results and make recommendations for further consideration.

Brans and Mareschal (2005) provide elaborate guidelines for one iteration of PROMETHEE GDSS procedure comprising three phases:

- Phase I: Generation of alternatives and PMs
- Phase II: Individual evaluations by each DM
- Phase III: Global evaluation by the group

Phase I and Phase II are similar to that of the single DM case described earlier. When there are several DMs, Phase II could bring in several decision matrices (m x n), each one of them representing DMs' own PM evaluations. Each DM could be given a different decision power, represented by a non-negative weight, ω_r (r = 1,2,….,R) so that: $\sum_{r=1}^{R} \omega_r = 1$.

Phase III deals with the net flow vectors, $(\Phi_1, \Phi_2,\ldots\ldots,\Phi_r,\ldots\ldots,\Phi_R)$, of all the DMs, which simplifies to a (m x R) matrix shown in the overview of PROMETHEE GDSS procedure in Figure 2.6. Each column (referred to as criteria in the methodology) of this matrix represents a point of view of a particular DM. Each of these criteria has a weight ω_r and an associated generalised criterion, Type III (e.g. $p = 2$) so that the preferences allocated to the deviations between the $\Phi_r(.)$ values will be proportional to these deviations. A global PROMETHEE II ranking and the associated GAIA are then computed. As each criterion is representing a DM, the conflicts between them are clearly shown in the GAIA plane.

If the conflicts among DMs are identified as very sensitive, Brans and Mareschal (2005) propose to review the following aspects of the problem as a feedback:

- Weightings given to the DMs,
- Individual evaluations,
- Set of PMs,
- Set of alternatives, and
- Initial problem formulation to include an additional stakeholder (DM) such as a social negotiator or government mediator.

Among other capabilities of *Decision Lab 2000* software package, it incorporates the PROMETHEE GDSS procedure as explained above. A detailed explanation of the group decision-making capabilities of *Decision Lab 2000* is given in Section 5.3.

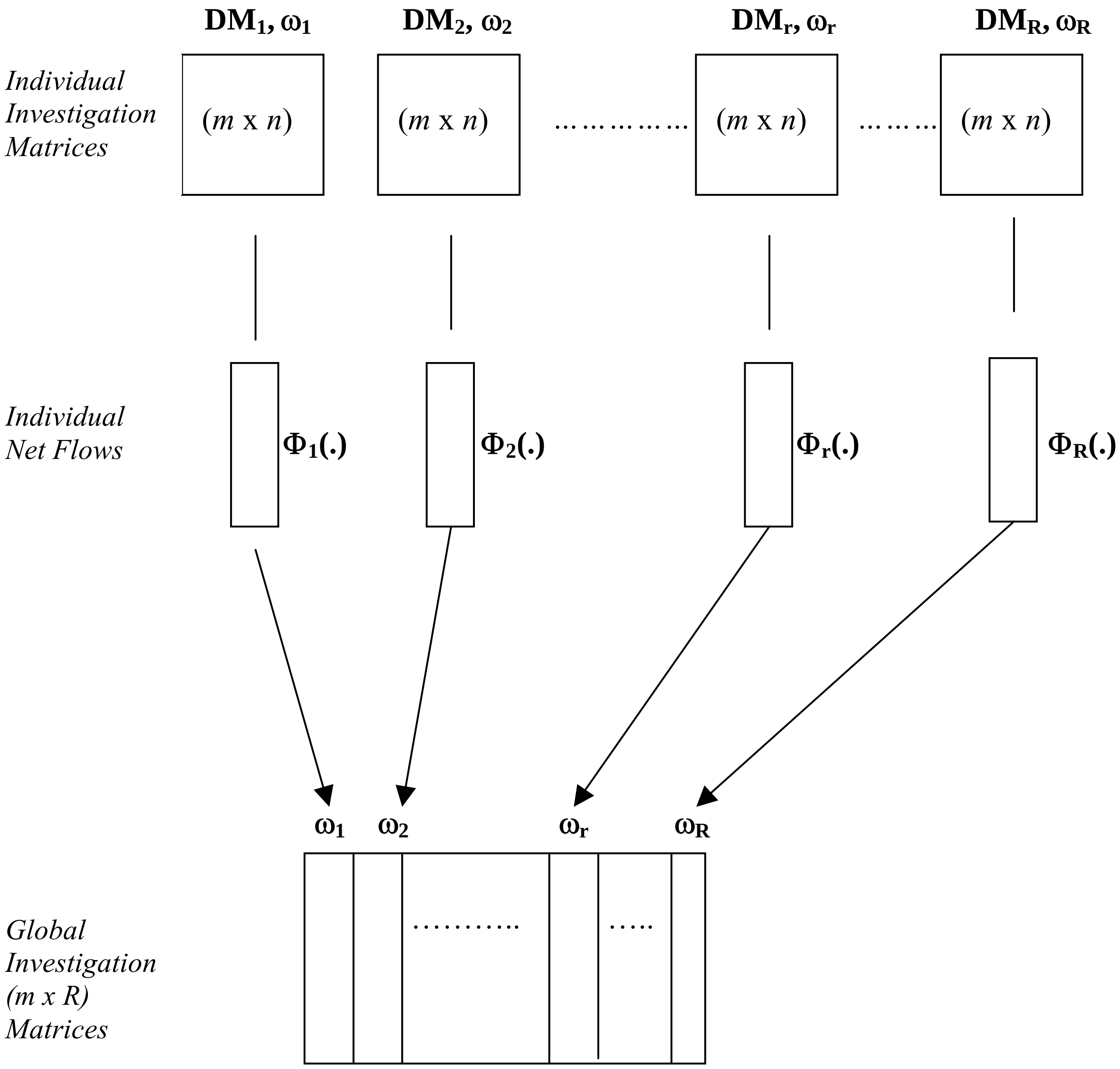

Figure 2.6: Overview PROMETHEE GDSS Procedure
(Source: Brans and Mareschal 2005)

2.8 Summary

As opposed to the single objective optimisation, the Multi-Criteria Decision Aiding (MCDA), which considers multiple objectives, in general, does not yield a single solution, which could be considered as the best alternative in terms of all the objectives simultaneously. Instead, MCDA gives the Decision Maker (DM) with some tools in order to enable him/her to advance in solving a decision problem where several (often conflicting) points of view must be taken into account. MCDA also provide an important contribution to the practical decision making process by facilitating to incorporate the subjectivity and real life experience of the DM, paving the way to more transparent and realistic analysis.

Discrete Multi-Criteria Decision Aiding (DMCDA) involves a finite set of feasible alternatives, a family of system PMs and preference judgements of the DM. First scientific treatment of MCDA date back to the World War II period, and since then many MCDA techniques have been proposed in the literature. A survey of available MCDA methods was presented with particular focus on the DMCDA methods. The multi-attribute utility based methods and outranking methods are discussed in detail with their key concepts, general applications and water resources applications. The utility-based methods aggregate the different points of view into a unique global value function with the aid of utility functions that must subsequently be optimised. Although the utility-based methods give more reliable results than the outranking methods, from a practical point of view, the process of deriving utility functions is considered long and tedious, which could also lead to inconsistent responses. In contrast, the outranking methods first aim to build an outranking relation, which presents the DM's established preferences with available data. The exploitation of outranking relation is conducted then, in order to help the DM to arrive at a decision.

The process of DMCDA starts with the evaluation of the system performance for the available alternatives. Then the DM's preference judgements are introduced into the analysis. The DM preferences are often considered to have a great influence on the final decision, at the same time, bringing in some uncertainty into the decisions.

A survey of the numerous software packages that have been developed and are still in use to aid the DMCDA problems is presented. These MCDA software tools built into decision support systems could continue to provide the necessary support for the water resource managers to systematically incorporate the stakeholder preferences in the decisions and to arrive at rational operational decisions through exploration and learning. ELECTRE and PROMETHEE are two popular outranking methods that proceed through interactive fixing of preference parameters. The PROMETHEE outranking approach with its current software tool *Decision Lab 2000* is selected for this study primarily because of its transparent computational procedure and simplicity. Its group decision-making features are utilised in the case study problem. The computation procedure involved in PROMETHEE/GAIA methodology is presented with the PROMETHEE GDSS (Group Decision Support System), which extends PROMETHEE methodology into its group decision-making capabilities.

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Chapter 3: Evaluation of Alternative Operating Rules for Urban Water Supply Systems

3.1 Introduction

The coordinated operation of multi-purpose, multi-reservoir water supply systems is typically a complex decision-making situation involving many variables, many objectives, considerable risk and uncertainty. The water resource managers are continuously challenged to meet various objectives (often conflicting) while complying with all legal contracts, agreements and traditions affecting water allocation and use. This chapter details some past practices in reservoir operations documented in literature and a methodology for evaluation of urban water supply system performance under alternative operating rules.

In light of fulfilling various priority objectives related to water supply system operations, the water resources managers often find that there are quite a number of alternative ways of operating the system (operating rules). These alternative operating rules satisfy the priority objectives to different extents. Therefore, it is difficult to make a rational judgement based on their intuition as to:

- which priority order of the objectives would suit best to all the stakeholders or
- which operating rule would be the closest match in meeting those objectives.

The evaluation of alternative operating rules in terms of the system performance often facilitates this judgement. The complexity of the evaluation process increases significantly with the number of alternatives and the number of system Performance Measures (PMs) that had been involved in prescribing the system performance. However, referring to many practical advances in science and technology, such as modelling and data base availability and access, Loucks and Gladwell (1999) state that the water resources mangers and the stakeholders have now been able to consider their individual preferences and a large number of PMs over complex systems for longer time frames than was possible in the past.

Several comprehensive state-of-the-art reviews of past research in reservoir operation models are given in Yakowitz (1982), Yeh (1985), Wurbs (1993) and Labadie (2004). Labadie (2004) states that the descriptive simulation models are useful tools in answering *what if* questions regarding the system performance of alternative operating strategies. He further states that the simulation models are ill-suited in prescribing the best or optimum strategies when flexibility exists in coordinated system operations. In contrast, the prescriptive optimisation models offer an expanded capability to systematically select optimal solutions, or families of solutions, under agreed upon objectives and constraints for multi-purpose reservoir systems. Optimisation models often compute the releases that optimise an objective function without directly addressing the finer details of the operating rules.

Although several different objectives will typically be of concern in a particular reservoir-system-analysis study, an optimisation model can normally incorporate only one objective function (Wurbs 1993). Despite the potential for the use of optimisation in real-time multi-reservoir operations and several decades of intensive research on their applications, many authors have reported a continuing gap between theoretical developments and real-world implementations of optimisation models (Labadie 2004; Oliveira and Loucks 1997; Wurbs 1993; Yeh 1985). Labadie (2004) notes some possible reasons for this disparity as follows:

- Many reservoir system operators are sceptical about models purporting to replace their judgement and prescribe solution strategies and feel more comfortable with use of existing simulation models.
- Computer hardware and software limitations in the past have required simplifications and approximations that operators are unwilling to accept.
- Optimisation models are generally mathematically complex than simulation models, and therefore more difficult to comprehend.
- Many optimisation models are not conducive to incorporating risk and uncertainty.
- The enormous range and varieties of optimisation models create confusion as to which to select for a particular application.
- Some optimisation methods such as dynamic programming often require customised program development.

- Many optimisation methods can only produce optimal period-of-record solutions rather than more useful conditional operating rules.

One of the modern ways of approaching planning and management of complex water resources systems is through systems analysis; the identification, analysis and evaluation of the interactions of all the components of the system in space and time (Labadie 2004; Wurbs 1993; Yeh 1985). To this respect, simulation models are widely used by water authorities around the world for planning and management of multi-reservoir urban water supply systems (Diba et al. 1992; Perera and James 2003). Although the simulation models do not provide the 'optimal' operation over the planning period, they may attempt to provide an optimal solution through 'optimal' operating rules. Perera and Codner (1996) point out that, with simulation models, it is very important to adequately capture the system behaviour under realistic operating rules so that near-optimal operation could be identified while providing important simulation results for the planner.

Among the many simulation models which have been customized for site specific conditions are the Colorado River Simulation System - CRSS (Schuster 1987) and Potomac River Interactive Simulation Model - PRISM (Palmer et al. 1980), while most of the other customized models have simply not been reported in the literature (Wurbs 1993). There is also substantial usage of public domain, general purpose models such as HEC-3 (Hydrologic Engineering Centre 1981), HEC-5 (Hydrologic Engineering Centre 1989), IRIS (Loucks et al. 1987) and RiverWare (Zagona et al. 2001). WASP (Kuczera and Diment 1988), WATHNET (Kuczera 1990; Kuczera 1992) and REALM (Diment 1991; Perera and James 2003; Perera et al. 2005) are some popular general purpose simulation models that have been developed in Australia. However, WASP is no longer used by the Australian water industry. Currently, REALM (**RE**source **AL**location **M**odel) has been adopted as a modelling standard for use in water supply planning and management in the States of Victoria, South Australia and Western Australia (Perera and James 2003).

Derivation of operating rules for multi-purpose, multi-reservoir water supply systems has become increasingly more complex and dynamic since it had been associated with many competing objectives related to social, economic, environmental and other requirements of the stakeholders. Usually, when there are many stakeholders involved in decision-making, such as resource mangers, water users, environmental interest groups etc., they have different priorities (often conflicting) on these objectives. Therefore, the need for describing and evaluating a system in terms of a set of measurable PMs is seen as important in making transparent decisions in water resources.

Section 3.2 describes the various practices adopted in the past to operate multi-purpose, multi-reservoir urban water supply systems and discusses how these system specific practices became established and documented later as standard operating rules for a particular system. Restriction rule curves, target storage curves and other operating rules are also discussed here with particular reference to the REALM headworks simulation model, which is used in this study.

Section 3.3 describes the system specific considerations on deciding a set of system PMs and a methodology for evaluating alternative operating rules using these system PMs.

This study used the REALM water supply headworks simulation model of the Melbourne water supply system to analyse and compute the system PMs on sixteen pre-defined alternative operating rules (for Melbourne system). A detailed description of REALM is given in Section 3.4.

Section 3.5 introduces the case study on Melbourne water supply system, with its system description and the current operating rules. For purpose of illustrating the generation of alternative operating policies in the case study, only four areas of system operations were considered in detail, i.e. demand restrictions policy, pumping/treatment at Sugarloaf reservoir, hydropower generation at Thomson and Cardinia reservoirs and minimum passing flows in Yarra river and Thomson river. Therefore, a description each of these particular operations is included in this section. The generation of sixteen alternative operating rules, the identification and definitions of performance measures, the data used in the case study and finally, the system performance evaluations in the form of a decision matrix are also presented in here.

3.2 Operating Rules for Multi-Reservoir Urban Water Supply Systems

As discussed in Section 3.1, the multiple objectives and the various stakeholder interests in water resources bring forward many solutions to the decision problem of deriving operating rules for a particular water supply system. Possibly due to this complexity, in practice, the operating rules for many multi-reservoir water supply systems are derived from heuristic approaches which are based on rules-of-thumb, rule curves, operator experience and judgement or various other assessments applied to both quantitative and qualitative historical information (Westphal et al. 2003).

Oliveira and Loucks (1997) note that defining effective operating rules for a particular water supply system is a challenging task, especially those that apply to multiple reservoirs serving multiple purposes and objectives. While pointing out that optimisation models are playing a minor role in identifying possible real-time reservoir operating rules, they report that many reservoir systems are still managed based on fixed predefined operating rules. Nevertheless, such models can be used for planning to help identify and evaluate alternative operating policies for fixed or predefined goals or objectives. They further state that in most cases, these predefined operating rules have been derived from operator experience or from trial-and-error simulation studies, and most of those have become very efficient over time. However, in spite of considerable past research on multi-reservoir system operations, they also highlight the need for a comprehensive negotiation and subsequent agreement among stakeholders for deriving improved and effective operating rules.

Operating rules for multi-reservoir urban water supply systems should specify how the total demand of a system could be met with the available supply of water in the system. For single purpose multi-reservoir systems, the operating policies are usually defined by rules that specify either individual reservoir desired (target) storage volumes or desired (target) releases based on the time of the year and the existing total storage volume in all reservoirs (Oliveira and Loucks 1997). A comparison of the individual reservoir storage targets to the actual storage volumes in each reservoir identifies which reservoirs should release water to meet the total system release target. Oliveira and Loucks (1997) also claim that having both system-wide release functions as well as individual reservoir storage volume target functions define a multiple-reservoir operating policy that permits the coordinated operation of the entire system.

Houck (1985) reports that for many reservoir systems in the United States, there exists a hierarchy of rules that regulate the operation of the system, and in general, these can be divided into three categories: (1) the rule curves, (2) a release schedule, and (3) operating constraints. The rule curves define the individual reservoir storage targets at different times of the year and a release schedule typically indicates the total release to be made from the reservoir system as a function of water available in the system and time of the year. There could also be other numerous system specific operating constraints that govern the operation of a water supply system. These could be detailed in terms of minimum river releases, hydropower commitments, meeting the minimum levels of service criteria (e.g. supply reliability, duration and severity of restrictions), amounts of river diversions etc.

Bower et al. (1962) suggest two rules for determining releases over time; a Standard Operation Policy (SOP) and a hedging rule. The SOP calls for the release in each period of the target release, if possible. If insufficient water is available to meet the target, the reservoir releases all the available water and becomes empty; if too much water is available, the reservoir can fill and spill the excess water. The hedging rule applies whenever there is a shortage of water and the marginal value of water is a decreasing function of the amount of water supplied. The hedging rule highlights that it is advantageous to accept a small current deficit in order to decrease the probability of a more severe water shortage in the future (Shih and ReVelle 1992).

Simulation models typically include mechanisms for detailed specification of operating rules (Wurbs 1993). Operating rules based on release rules and storage balancing rules are used in simulation models such as HEC-3 (Hydrologic Engineering Centre 1981), HEC-5 (Hydrologic Engineering Centre 1989) and IRIS (Loucks et al. 1987). The simulation models REALM (Diment 1991; Perera and James 2003; Perera et al. 2005), WASP (Kuczera and Diment 1988) and WATHNET (Kuczera 1990; Kuczera 1992) base their operating rules on ‘restriction rule curves’, ‘target storage curves’ and other operating constraints. Detailed explanations on the restriction rule curves, target storage curves and the other operating rules based on system constraints are given in Sections 3.2.1, 3.2.2 and 3.2.3 respectively, since REALM is used in this study.

3.2.1 Restriction Rule Curves

In most multi-reservoir urban water supply systems, the restriction rule curves form part of the overall system operation by way of supplying only a restricted demand at demand points during low flow periods. A typical set of 5-stage urban restriction rule curves is given in Figure 3.1. As explained in REALM User's Manual (Victoria University and Department of Sustainability and Environment 2005), these curves generally define the restriction entry trigger levels (level 0, level 1, level 2 etc.) with respect to the volume of the total system storage expressed either as absolute values or as percentages of the Average Annual Demand (AAD). Four intermediate zones are defined in Figure 3.1 between Upper Rule Curve (URC) and Lower Rule Curve (LRC). Each zone is associated with its restriction stage defined for a particular system, with an increasing harshness as the storage volume decreases.

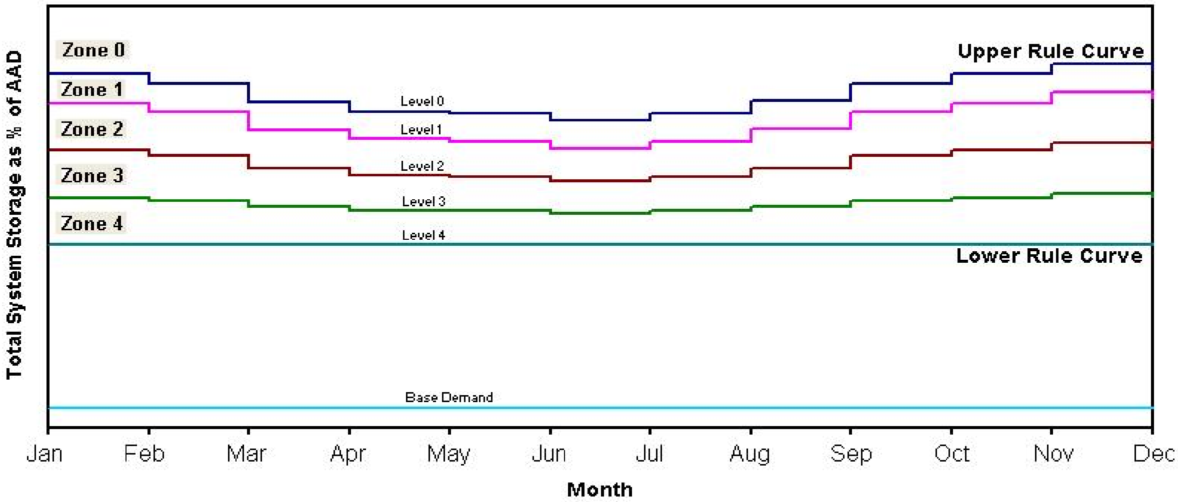

Figure 3.1: A Typical 5-Stage Urban Restriction Rule Curves
(Source: Victoria University and Department of Sustainability and Environment 2005)

When the storage volume is above the values indicated by the URC, then no restrictions are imposed on the water demand. At any particular month, the restrictions are imposed when the total system storage drops down below the level defined by the URC for that month. If the storage volume is below the values defined by the LRC, then the water demand is restricted to the ‘Base Demand’ (i.e. in-house water use). If the storage volume is in an intermediate zone, the demand is then restricted by an appropriate estimated percentage reduction defined for that zone; in this case the demand above the base demand is restricted.

The Melbourne system adopts a 4-stage demand restriction policy in which the regulatory measures are applied only to outdoor uses such as garden watering, vehicle washing etc. Once entered into a particular level (or stage) of restriction, the use of water for different purposes by different consumer categories is regulated through a set of established rules at each level of restriction and this information is passed on to the water users before imposing the restrictions on the supply. The harshness (or the severity) of these regulations increases as the level of restriction increases. In essence, the restriction rule curves indicate when to impose the regulations at each level of water restriction for a given month of the year.

3.2.2 Target Storage Curves

The target storage curves specify the preferred distribution of storage volume among individual reservoirs in a multiple reservoir system for a given total system storage (Kuczera and Diment 1988; Perera and Codner 1996). These target rules enable to force the necessary inter-reservoir transfers to distribute water in the system so as to supply the required demands at various demand points. The concept of target storage curves is widely used in the simulations models developed in Australia such as REALM (Diment 1991; Perera and James 2003; Perera et al. 2005), WASP (Kuczera and Diment 1988) and WATHNET (Kuczera 1990; Kuczera 1992).

Figure 3.2 illustrates typical target storage curves for a two-reservoir system. For a given total system storage S_T at a given month, the target storage curves specify the storage volumes at reservoirs 1 and 2 as S_1^* and S_2^* respectively, where the sum of S_1^* and S_2^* equals to S_T.

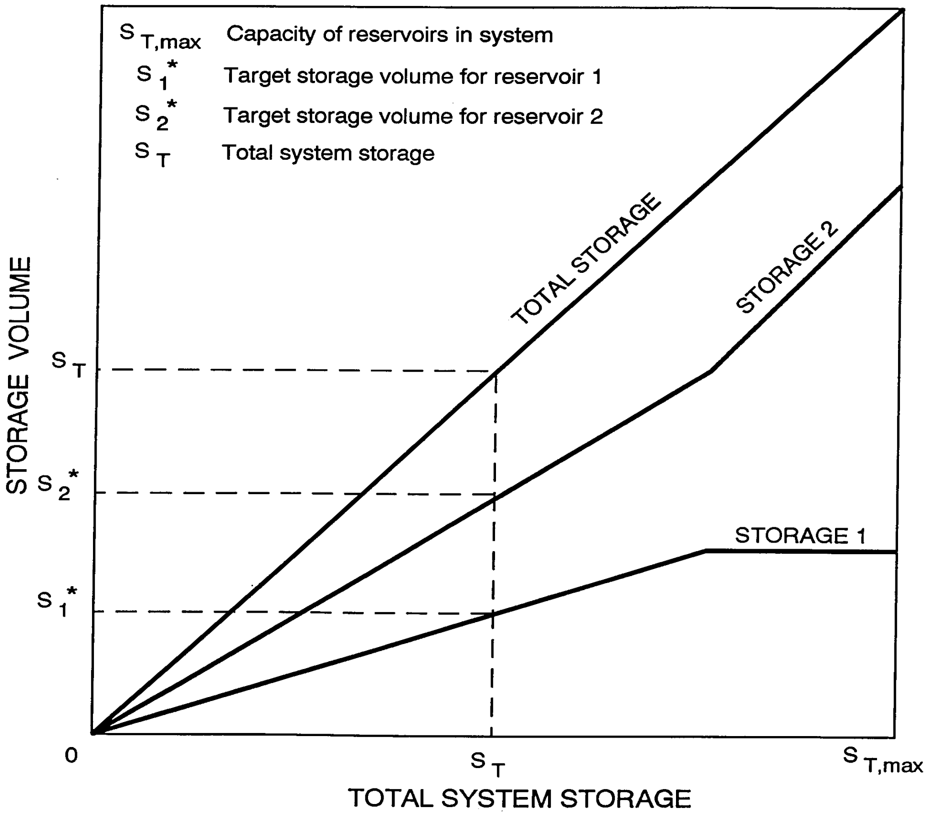

Figure 3.2: Target Storage Curves for a Typical Two-Reservoir System (Source: Perera and Codner 1996)

In REALM, different sets of target storage curves can be specified for different months of the year, and they attempt to achieve these target storage volumes at the end of each simulation time step. The target storage curves are defined for the whole range of total system storage giving preferred storage volumes of individual reservoirs. They can be optimal or otherwise.

In multi-reservoir simulation models, the interpretation of target curves is an important way of understanding how water can be stored in individual reservoirs at the end of each time step. When the inflow during a simulation time step is greater than the demand, the total system storage at the end of simulation time step increases and the target storage curves determine where this excess water should be stored (Perera and Codner 1996). However, it is widely acknowledged that in practice, the system operators often deviate from these rules to adapt to specific conditions, objectives or constraints that may exist at various times.

The REALM Melbourne water supply system model that was used by Melbourne Water (MW) in 2002-03 considered the target storage curves for both planning and operational purposes. However, as explained later in Section 3.4, the relative hierarchy of REALM give the least priority for satisfying the target storage curves. Therefore, the REALM outputs are not very sensitive to the target storage curves. Hence, the target storage curves were not used as a basis for deriving alternative operating rules for Melbourne system in the case study.

3.2.3 Other Operating Rules

The operating rules for multi-reservoir systems could also be defined through various other system variables such as hydropower generation, amount of stream diversions, amount of environmental flow releases etc. Most of these site-specific operating rules could be accommodated in simulation models by way of ‘hard-wiring’ the model to configure the specific requirements related to these other operating rules. An example of how REAM could make sure the environmental flow releases before meeting the urban demand is discussed in Section 3.4.

3.3 System Performance Measures and Decision Matrix

The integrated operation of urban water supply systems represents an approach to managing the system according to derived set of objectives with respect to long-term social, economic, environmental and supply sustainability considerations. These objectives usually stem from a single overall goal (such as sustainable management of the water resources) agreed upon by the stakeholders.

System Performance Measures (PMs)

Rogers et al. (2000b) state that the ultimate aim of evaluating the alternative operating rules is to develop a grasp of the relative effectiveness with which the selected alternatives meet the derived set of objectives. The objectives have their own merits, and must therefore be considered and evaluated using its own individual set of PMs.

There are two types of evaluations on the PMs discussed in the literature (Srinivasa Raju et al. 2000). Certain PMs are inherently numerical and can be assessed on a cardinal scale; they are described as '*quantitative PMs*'. There are other evaluations, which cannot be made on a numerical basis; these are described as '*qualitative PMs*'. Preferably, each PM should be quantitatively assessed, but if, as with some social and environmental PMs, they cannot be assessed on any cardinal scale, it should be possible to measure them qualitatively, on some graded, comparative scale. However, to facilitate the final analysis, many multi-criteria analysis procedures force these qualitative assessments eventually be converted into numerical values using some form of a rating system. Often a qualitative scale is simple and indicates PM evaluations such as very poor (or negative), poor (or below average), average (or neutral), good (or above average), or excellent (or most beneficial) with rating vales ranging from 1 to 5, respectively.

In an attempt to study the resource conflicts in the Colorado River Basin due to development and changing water use priorities, Flug et al. (2000) used a numerical rating scale to evaluate 29 natural resource related PMs (qualitative), which represented 7 objectives. Nine different flow release alternatives for the Colorado River system below the Glen Canyon Dam was considered in the analysis. Since the rating of natural resource PMs generally produces a matrix of non-commensurate values that could include a mix of qualitative statements and/or numeric values in a variety of units, they recommended a standard quantitative rating scale with values from 1 to 9 to evaluate each flow release alternative in terms of the PMs.

Most multi-objective analysis applications in natural resources management contain a mix of qualitative and quantitative PMs (Abrishamchi et al. 2005; Anand Raj 1995; Cai et al. 2004; Gershon et al. 1982; Joubert et al. 2003; Netto et al. 1996) with occasionally describing the objectives in all qualitative PMs (Nijkamp and Vreeker 2000; Srinivasa Raju et al. 2000) . When the decision aiding tools are built into decision support systems with simulation models being used to calculate the PM evaluations, it is common to have all quantitative PMs (Dunn et al. 1996; Rajasekaram and Nandalal 2005).

The set of PMs is usually determined by discussions with the DMs who have a good knowledge of the system and an understanding of the decision problem in hand. Once the PMs are determined, they will be used as 'standards of judging' in the case of alternatives being examined.

Roy (1996) explains that, a set of PMs is coherent if it satisfies the following three properties:

1. *Exhaustiveness* - Meaning that none of the PMs used to discriminate between alternatives has been forgotten. In this case the set is exhaustive if there exist no pairs of alternatives (*a*, *b*) that are tied according to all the PMs in the set and a Decision Maker (DM) can without hesitation say that '*a*' is better than '*b*' or '*b*' is better than '*a*'.

2. *Consistency* - The DM's global preferences should be coherent with the preferences with respect to each PM. If '*a'* and '*b'* are two alternatives between which the DM is indifferent (and especially if they achieve the same score for each PM), then the improvement in '*a*' according to one PM and/or degradation in '*b*' according to another PM does indeed imply '*a*' is better than '*b*'.

3. *Non-redundancy* - A set of PMs that satisfies the properties of exhaustiveness and consistency is non-redundant if removing one single PM leads to the rest of the set no longer satisfying the requirements of exhaustiveness and consistency.

According to Pomerol and Barba-Romero (2000), out of these three properties, '*exhaustiveness*' is very vital for the quality of any decision aid, and hence from the discussions with the DM, a complete set of PMs should be determined to express all the aspects to be considered in the decision. They further state that, the property of '*consistency*' is generally satisfied with a rational decision maker and the property of '*non-redundancy'* is desirable but the drawbacks which result from lack of it depend on the method of aggregation used; the greater the cardinality of the method, the greater the drawbacks are. The risk of redundancy could be in the form of attaching too much importance to a PM, which happen to feature two (or more) times in more or less closely similar forms (Pomerol and Barba-Romero 2000).

The interaction between the various objectives in multi-purpose reservoir operations could be explained by system PMs, which quantify the characteristics of reservoir system behaviour (Rhodes 1989). According to Piyasena (1998), the system PMs in relation to reservoir operation were studied by Hashimoto et al. (1982). With a single reservoir system, they describe the system performance with respect to the 'level of service', from three different viewpoints:

- How often the system fails (reliability)
- How quickly the system returns to a satisfactory state once a failure has occurred (resiliency), and
- How significant the likely consequences of failure may be (vulnerability)

They showed that high system reliability could normally be accompanied by high system vulnerability and therefore to achieve the best performance, the engineers and planners need to develop appropriate quantitative risk PMs that describe the undesirable events that may be experienced as a consequence of a particular operating policy decision.

Section 3.5.4 describes the selection of objectives and PMs for Melbourne water supply system case study. Discussions with MW officers and the points discussed above were considered in selecting four main objectives and eight quantitative PMs related to the case study.

Decision Matrix

The relative merit of each alternative operating rule is determined on the basis of its performance on each of the chosen PMs. As explained in Section 2.4, a decision matrix contains the PM evaluation with respect to each of the alternatives. These PM evaluations could either be derived by mathematical/simulation modelling or expert judgement of the professionals in the field. The Melbourne REALM headworks simulation model was used in the case study example to derive the decision matrix.

3.4 REALM Simulation Software

REALM is a generalised simulation computer software package origianlly developed by the (former) Department of Conservation and Natural Resources (Victoria), Australia in close conjunction with the water industry. Since then, there had been many enhancements in response to the suggestions and feedback from the users. Currently, REALM is adopted as the modelling standard for use in water supply planning and management in Victoria. The states of Western Australia and South Australia are also major users of REALM. A latest version of REALM can be downloaded free of charge from the Department of Sustainability and Environment (Victoria) website http://www.dse.vic.gov.au/vro/water .

Since this study has extensively used REALM to evaluate the alternative operating rules for Melbourne system, a comprehesive description of the model as well as its structure and configuration details related to urban water supply system modelling are presented below. Most of the following contents are extracted either from REALM User's Manual (Victoria University and Department of Sustainability and Environment 2005) or from Perera and James (2003).

REALM requires three main input data files; streamflow file, demand file and sytem file. The streamflow file contains the system inflow details and climatic data. System inflows are the unregulated streamflow that is available for harvesting. Climatic data in the streamflow file (e.g. temperature, rainfall, climatic indices) are used to model reservoir evaporation losses and seasonally adjusted monthly demands from the AAD forecast values. The demand file contains the unrestricted demands for each demand zone in the water supply system. REALM configures the actual system using a set of '*nodes*' connected by '*carriers*'. The system file contains the information on nodes and carriers in the network (e.g. capacity constraints, transfer priorities etc.) and long-term operating rules controlling inter-reservoir transfers and demand restrictions.

In urban water supply modelling, REALM can configure five types of nodes:

- Reservoir nodes which can explicitly model maximum capacity, dead storage, evaporation and reservoir inflow
- Demand nodes to model urban supplies

- Stream junction nodes to model river confluences which can have a stream inflow at the junction
- Pipe junction nodes where two or more pipes meet
- Stream terminator nodes to configure the terminating points of the water supply system

The above nodes are connected by either river or pipe carriers. Both these carriers, are distinguished by the way their capacities are modelled. The first type is the '*fixed capacity carrier*' with a constant monthly maximum capacity. The second type is a '*variable capacity carrier*', in which the capacity of the carrier is dependant on the values of one or several system variables. These carriers can explicitly model minimum flows, maximum capacities and transmission losses. In addition, by assigning a set of user-defined '*penalties*' (usually in the order of 0 to 1000) to the carriers, the preffered flow distribution of the water supply sytem can be modelled. When there are two or more flow paths between two nodes, flow will first occur in the carrier with the lowest penalty upto its capacity, then the carrier with the next higher penalty will be used and so on until the required flow is received by the downstream node.

REALM models the harvesting and bulk distribution of water resources within a water supply system. Similar to other simulation models, mass-balance accounting procedures are used at nodes, while the movement of water within carriers is subjected to capacity constraints. It uses fast network linear programming algorithm to optimise the water allocation within the system for each time step of a simulation period using user-defined penalties and operating rules. The operating rules are defined by restriction rule curves, target storage curves and other priority releases such as environmental flows. During each simulation time step, the model attempts to satisfy the following water assignment criteria (in decreasing order of priority) when allocating water within the system (Victoria University and Department of Sustainability and Environment 2005):

- Satisfy evaporation losses in the reservoirs
- Satisfy transmission losses in carriers
- Satisfy all demands (which may be restricted), to maximise supply reliabilty
- Minimise spills from the system, to maximise the yield

- Satisfy instream requirements defined by minimum capacity of carriers
- Ensure that the end-of-season storage volumes meet the reservoir targets

The above water assignment criteria are achieved through the ‘*system penalties*’ in REALM, which are several orders of magnitude greater than the user-defined penalties. These system penalties have in-built default values that cannot be changed by the user. However, any other operating rule contradicting the above hierarchy can also be modelled by using varaible capacity carriers with very large positive or negative penalties. One such example as explained in Perera and James (2003) is when it is required to meet the environmental flows before satisfying the urban (restricted) demands which is contradictory to the REALM specified hierarchy of water assignment criteria mentioned above. This is achieved by turning off the minimum flow attribute of the carrier and creating a variable capacity carrier parallel to the above carrier, but with a capacity equal to the environmental flow and an appropriate large negative penalty (e.g. -53,000,000). A description of Melbourne system REALM model used by Melbourne Water is given in Section 3.5.3.

3.5 Case Study - Melbourne Water Supply System

It has been long recognized by the urban water industry in Australia including Melbourne, that their ability to meet future demands for water is doubtful especially due to increase in population in urban areas. Recent protracted dry conditions across most of Victoria have also aggravated the problem by highlighting the limited availability of water resources, particularly during drought periods (Water Resources Strategy Committee 2001).

The optimal operation of the system in the long and short term could be achieved through a range of options, which meet the operational objectives to different levels. However, the multiple facets of these operational objectives often conflict with each other, making it difficult to intuitively decide on an optimum operating rule. As described in Section 3.2, the operating rules are commonly being defined by the water authorities in terms of drought response initiatives through the severity and timing of water restrictions (i.e. restriction rule curves), the spatial distribution of storage volumes of the reservoirs for a given total system storage (i.e. target rule curves) and/or other variables in the water supply system. In optimising the system operations, this study considered sixteen alternative operating rules focussing on eight system PMs and stakeholder preferences on those PMs. However, an emerging issue is the extent to which stakeholder preferences can be included in the decision process.

3.5.1 System Description

MW operates and maintains a multi-reservoir system that provides water supplies to a population of about 3.7 million people in Melbourne. The 2002 average annual water consumption for Melbourne is estimated at around 490,000 Ml and the estimated long-term average annual population growth is about 0.6% (Water Resources Strategy Committee 2002a). The system currently has a total capacity of 1,773,000 Ml and utilizes 9 major reservoirs including 6 harvesting reservoirs and 3 seasonal balancing storage reservoirs. A detail map of the Melbourne water supply system is given in Appendix B (Yurisich and Rhodes 1997). Figure 3.3 schematically shows all the harvesting reservoirs, seasonal storage reservoirs, major inflows and transfers between reservoirs.

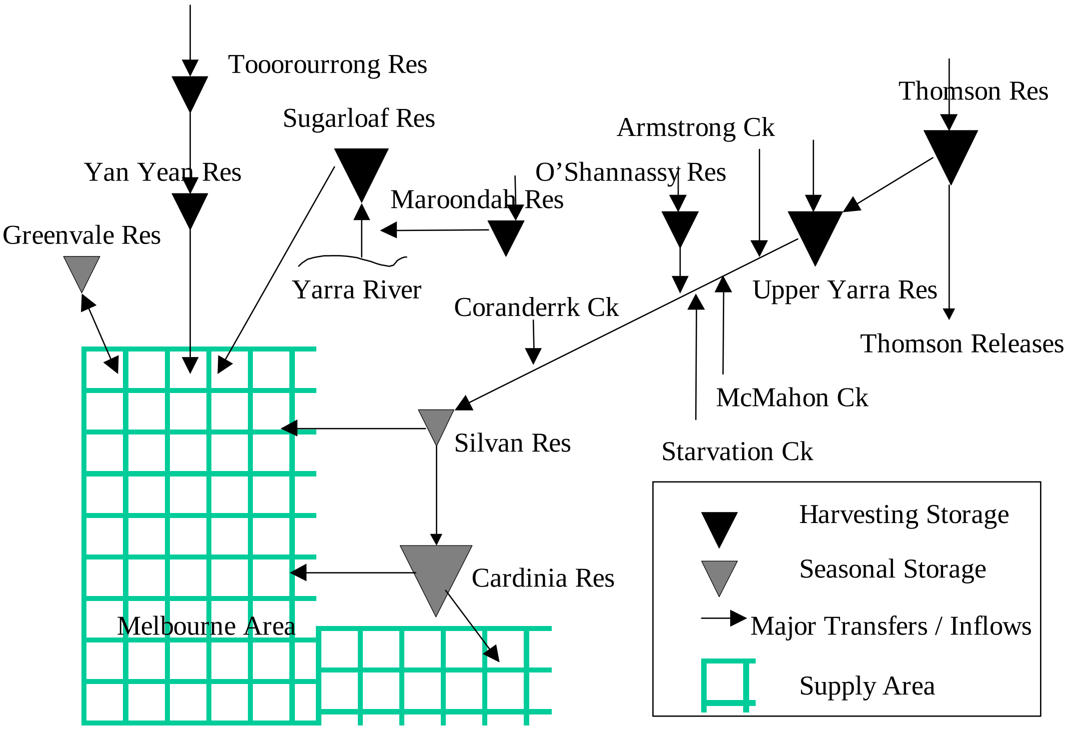

Figure 3.3: Schematic Diagram of Melbourne Water Supply System
(Source : Perera et al. 2005)

The Melbourne water supply system comprises a headworks system, seasonal storages and a seasonal transfer system. The headworks system includes:

- Thomson reservoir
- Upper Yarra reservoir
- Maroondah reservoir
- O'Shannassy reservoir
- Sugarloaf reservoir
- Yan Yean reservoir
- Northern catchments including the Yarra tributaries (Amstrong, McMahon and Starvation creeks), Wallaby and Silver creeks

These harvesting reservoirs receive water mainly from uninhabited and forested catchments around Melbourne. The three seasonal storages are Silvan reservoir, Cardinia reservoir and Greenvale reservoir.

Water from the harvesting reservoirs is transferred via the seasonal transfer system (pipelines and aqueducts) primarily by gravity flows to seasonal storages that are located closer to Melbourne metropolitan area, for supply to the three retail water companies, City West Water (CWW), South East Water (SEW) and Yarra Valley Water (YVW). A detail description of the Melbourne's water supply system is given in Yurisich and Rhodes (1997).

The operating guidelines for Melbourne water supply system is documented in 'Bulk Water Entitlement Operating Rules', a report prepared for Melbourne Water by Wise Technology Management (1997). This report combined the various analytical studies carried out in the past and the system operators' experience. The guidelines are detailed separately in the report, for the headworks system, the seasonal storages and the seasonal transfer system. The actual operation of the system takes place according to an 'Annual Operating Plan' based on the general guidelines detailed in the above report. The current operating rules discussed in Section 3.5.2 are based on the above 'Bulk Water Entitlement Operating Rules'.

3.5.2 Current and Alternative Operating Rules

As stated in Section 3.1, for demonstrating the case study example, four areas of system operations were identified through the discussions with MW officials, where possible variations appeared to bring about an improvement to the current system operations. Therefore, this study mainly focussed on those four areas of system operations to generate alternative operating rules. They are the:

- Demand restriction policy
- Pumping / treatment at Sugarloaf reservoir
- Hydropower generation at Thomson and Cardinia reservoirs and
- Minimum passing flows in Yarra river and Thomson river

In generating the alternative operating rules, one variation each of the above system operations was considered.

3.5.2.1 Demand Restriction Policy

To manage the water supplies in periods of drought, the metropolitan water authorities have developed a Drought Response Plan (DRP) for Melbourne, which details certain stages of demand restrictions for consumers (www.melbournewater.com). In Melbourne's DRP, a drought is defined as a period during which:

- There is insufficient available supply of water to meet expected demands due to extreme weather conditions and/or lower than expected inflow conditions to the water supply catchments and/or
- The water authorities believe that a reduction or restriction in use is necessary to avoid future shortages

It further states that, one or more of the following conditions may accompany a drought:

- Lower than expected storage
- Lower than expected streamflows into storage reservoirs
- Higher than expected demands due to prolonged periods of below average rainfall and/or above average temperatures

The DRP provides an ‘early warning’ and a ‘voluntary reduction’ period where a call is made for voluntary reduction of water consumption. This is followed by a 4-stage demand restriction policy, which specifies progressive restrictions on outdoor water use depending on the total storage volume in the reservoirs (TSS). As given in 2002-03 DRP, for each month of the year, restriction entry trigger levels as % TSS are shown in Table 3.1.

Table 3.1: 2002-03 DRP Restriction Entry Trigger Levels (as % TSS values)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stage 1	52	51	48	46	46	45	46	48	51	52	54	53
Stage 2	45	44	42	41	40	40	40	42	44	45	46	45
Stage 3	37	36	35	35	35	34	35	36	36	37	37	37
Stage 4	29	29	29	29	29	29	29	29	29	29	29	29

The four stages of restriction range from the least severe (Stage 1 – mild restrictions) to the most severe (Stage 4 – critical restrictions). Each stage of restrictions is estimated to correspond with an expected percentage saving in total metropolitan water consumption as shown in Table 3.2 for 2002-03 DRP. Therefore, when the most severe restrictions (Stage 4) are imposed, the maximum restrictable demand, i.e. 22% of AAD is saved. The remaining 78% is the ‘base demand’, which is non-restrictable. As also explained in Section 3.2.1, the Stage 1 and Stage 4 entry trigger points define the URC and LRC respectively (Table 3.1).

Table 3.2: Expected Percentage Reductions in Demand for each Restriction Stage

Restriction Stage	Annual Metropolitan Saving (as % AAD)
Stage 1	6%
Stage 2	11%
Stage 3	16%
Stage 4	22%

Due to the severe dry conditions, which prevailed across most parts of Australia since 1997, the water authorities introduced some permanent water saving measures for Melbourne in 2005 on top of the 4-Stage demand restriction policy. This was made effective from March 2005 to apply all year round with an expected total saving of 2%

of the average annual demand. While the drought conditions arebecoming worse, currently, the regulatory measures in each stage of restriction are reviewed monthly (www.melbournewater.com). In these monthly reviews, weather forecasts, water consumption, seasonal factors and rainfall in catchments are all taken into consideration.

Variation to 2002-03 Demand Restriction Policy

The current restriction entry trigger levels were slightly modified to generate the variation with respect to the demand restrictions. The variation has the following modifications applied to the restriction entry trigger levels of the 2002-03 DRP's 4-Stage demand restriction policy, the % savings at each restriction level remaining unchanged:

- Restrictions equivalent to current Stage 1 with a 6% saving at all times (i.e. URC/Stage 1 is shifted upwards to reach 100% TSS) – this is similar to permanent saving measures but with a higher saving and
- Stage 2 restrictions are imposed when the %TSS reach the Stage 2 trigger values (these are the 2002-03 DRP Stage 1 values) indicated in Table 3.3, with a 11% saving.
- No change to Stage 3 and Stage 4 curves

Table 3.3: Restriction Entry Trigger Levels in the Variation (as % of TSS values)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stage 1	100	100	100	100	100	100	100	100	100	100	100	100
Stage 2	52	51	48	46	46	45	46	48	51	52	54	53
Stage 3	37	36	35	35	35	34	35	36	36	37	37	37
Stage 4	29	29	29	29	29	29	29	29	29	29	29	29

This study considered the 2002-03 DRP (i.e. before permanent water saving measures came to effect). The 2002-03 DRP regulatory measures imposed in Stage 1, Stage 2, Stage 3 and Stage 4 restrictions are given in Appendix C. The 2002-03 DRP restriction entry trigger levels with the variation are graphically shown in Figure 3.4.

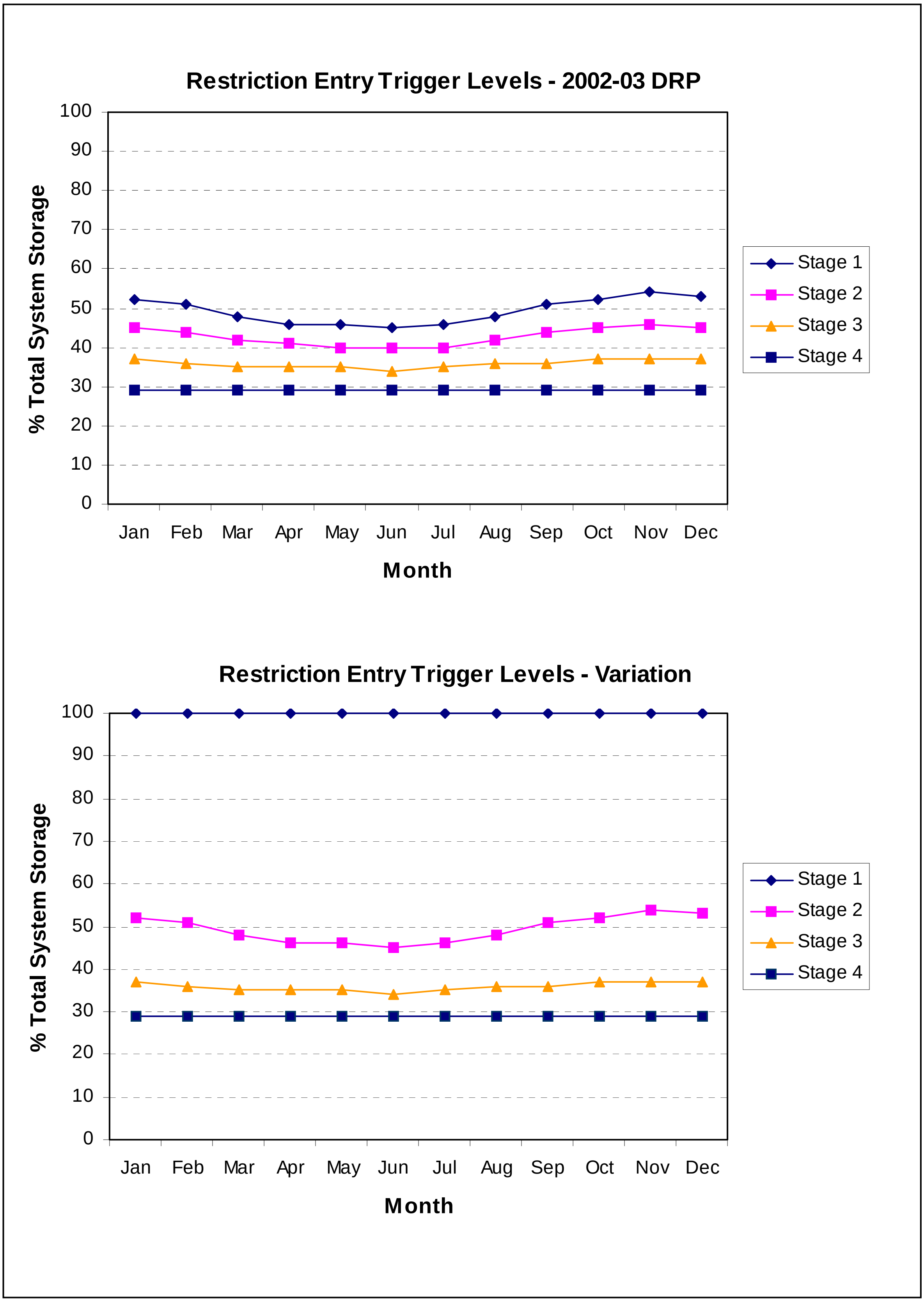

Figure 3.4: Restriction Entry Trigger Levels: 2002-03 DRP and the Variation

3.5.2.2 Pumping and Treatment at Sugarloaf Reservoir

Sugarloaf reservoir and Winneke Water Treatment Plant (WTP) were added to Melbourne system in the early 1980's to supplement the summer peak demand and later used to assist in drought recovery of Thomson reservoir (Wise Technology Management 1999). Being an off-river storage without its own catchment, the Sugarloaf reservoir is mostly dependent on the limited volume of water pumped every year from the Maroondah aqueduct and Yarra river at Yering Gorge. This water is then fully treated at WTP to provide high quality drinking water at a higher operating cost, before releasing to the transfer system.

The combined cost of treatment and electricity to run the Yering Gorge pumps is a key consideration in managing the inflows to the system through Sugarloaf reservoir. Winneke water is therefore not considered as a preferred source because of these associated pumping and treatment costs.

According to 'Melbourne Water System Description' (Yurisich and Rhodes 1997), when pumping water from the Maroondah aqueduct and the Yarra river, aqueduct water is preferred because it requires less-head pumping and is higher quality water than harvested from the Yarra river. There are 4 pumps at Yering Gorge, with maximum capacities of 250 Ml/d each; they are usually operated at around 210 Ml/d. Due to water quality and electricity cost considerations, the general operating rules for pumping water into Sugarloaf reservoir has the following priorities:

1. Pump during off-peak electricity periods from the aqueduct only.
2. Pump off-peak from both the aqueduct and the river.
3. Pump off-peak and peak from the aqueduct and off-peak from the river.

The operation of Winneke treatment plant is detailed in 'Bulk Water Entitlement Operating Rules' by Wise Technology Management (1999) and is based on the TSS and the Melbourne's water demand. With current demand levels, a considerable amount of water is supplied to the system through the WTP. Under normal operations, it ranges from 60 - 130 Gl/yr.

According to 'Bulk Water Entitlement Operating Rules' (Wise Technology Management 1999) there are four clarifiers at the WTP each with a nominal capacity of 150 Ml/d and these clarifiers work most effectively in the range 200 - 400 Ml/d. A peak flow of 550 Ml/d can also be sustained for about 24 hours. The WTP has a sustained output limit of 450 Ml/d, which corresponds to 4 clarifiers in operation.

Variation to Pumping and Treatment at Sugarloaf Reservoir

- WTP capacity was increased from about 450 Ml/d to 560 Ml/d by adding one more clarifier with a nominal capacity of 150 Ml/d.

3.5.2.3 Hydropower Generation at Thomson and Cardinia Reservoirs

A limited amount of hydropower is generated as a by-product at two locations, Thomson reservoir and Cardinia reservoir, when the water is released or transferred to meet environmental requirements or urban demands. Hydropower is generated at Thomson reservoir, by passing the required environmental flow releases through the hydropower station.

Hydropower generated at Cardinia reservoir relies on the water transferred from Silvan reservoir to Cardinia reservoir and is used for meeting the urban demand whereas the water used for hydropower generation at Thomson reservoir subsequently leaves the system as environmental flows without being used to meet the urban demand. As detailed in 'Bulk Water Entitlement Operating Rules' (Wise Technology Management 1999), MW is obliged to pass a minimum of 93 Gl/year through the Cardinia hydropower station with Silvan water flowing into Cardinia reservoir.

The usable capacity of Thomson reservoir (i.e. 1,068,000 Ml) is shared between MW, Southern Rural Water (SRW)'s irrigation requirements and environmental passing flow requirements. The MW's share of Thomson reservoir, 1,023,000 Ml is primarily used to supply Melbourne. The Thomson hydropower plant is located downstream of the dam and generally, all SRW's irrigation flows and environmental passing flows are released through the hydropower plant, except when the required releases exceed the hydropower plant's capacity or the hydropower plant is off-line for maintenance. The flows through the hydropower plant vary from 0 to a maximum of 480 Ml/d.

According to MW internal report 'Investigation of Alternative Thomson Hydro Release Rules' (Melbourne Water Corporation 1999), the flow releases through the Thomson hydropower plant depend on the MW share of Thomson storage volume, the past 6 months inflow to Thomson reservoir and the climatic outlook.

Two sets of 'Base' rules are applied during May-October and November-April months. Also, a "Drought Release" operating principle and a "Storage Recovery" operating principle cover the security of supply issues resulting from drought periods. "Base" operating rules are shown in Table 3.4(a) and Table 3.4(b), and the "Drought Release" operating principle is given in Table 3.4(c), as summarized in 'Thomson Hydropower Plant Operating Rules: REALM Configuration" (Melbourne Water Corporation 2002a).

Table 3.4(a): November - April "Base" Hydro Operating Rules

Melbourne's Storage Volume held in Thomson Reservoir (Ml)	Operating Release (Ml/d)	Comments
< 770,000	Minimum release (Environmental & irrigation flows only)	As per Thomson flow sharing agreement
770,000 - 850,000	225	11.5 hours per day - peak only
850,000 - 950,000	370	17 hours per day
> 950,000	480	24 hours operation
Note: These rules apply unless minimum environmental and irrigation releases were made in October and otherwise the Table 3.4(b) rules apply to all months as per the "Storage Recovery Principle**" given below Table 3.4(c).		

Table 3.4(b): May - October "Base" Hydro Operating Rules

Melbourne's Storage Volume held in Thomson Reservoir (Ml)	Operating Release (Ml/d)	Comments
< 850,000	Minimum release (Environmental & irrigation flows only)	As per Thomson flow sharing agreement
850,000 - 950,000	225	11.5 hours per day - peak only
> 950,000	370 or 480 subject to streamflow and climate outlook*	17 or 24 hours per day

Note: These rules apply:

1. From May to October unless cumulative Thomson reservoir inflows during the previous 6 months are below the 10th percentile when the "Drought Release Principles" in Table 3.4(c) are triggered or
2. All year as per "Storage Recovery Principle**" [as given below Table 3.4(c)], if minimum environmental and irrigation releases were made in October.

*370 Ml/d if the seasonal climate outlook indicates a strong bias towards drier than average conditions; 480 Ml/d otherwise

Table 3.4(c): May - October "Drought Release" Hydro Operating Principles

Melbourne's Storage Volume held in Thomson Reservoir (Ml)	Operating Release (Ml/d)	Comments
< 900,000	Minimum release (Environmental & irrigation flows only)	As per Thomson flow sharing agreement
900,000 - 950,000	225	11.5 hours per day - peak only
> 950,000	370 or 480 subject to streamflow and climate outlook*	17 or 24 hours operation

Note: These rules apply from May to October if the cumulative Thomson reservoir inflows during the previous 6 months are below the 10th percentile. If triggered, these principles apply until November when the "Storage Recovery Principle**" as given below, is invoked.

*370 Ml/d if the seasonal climate outlook indicates a strong bias towards drier than average conditions; 480 Ml/d otherwise

**Storage Recovery Principle

Following a period where minimum releases have been made due to low Thomson storage conditions, the hydro operating rules specified in Table 3.4(b) may apply to all months until Melbourne's storage volume exceeds 950,000 Ml. The rules specified in Tables 3.4(a) and 3.4(b) then apply as per normal conditions.

The drought release and storage recovery operating principles may be varied subject to consideration of:

- Adverse or favorable seasonal climate outlooks
- Prevailing streamflow conditions within the Melbourne supply system, catchment conditions, and total system storage volume available to Melbourne
- Operational changes or outages within the Melbourne supply system
- Changes in water allocation principles within the Melbourne supply system or Thomson catchment

Variation in Hydropower Generation

- The amount of water released through Cardinia hydropower plant is maintained at current levels
- Hydropower generation at Thomson Reservoir is reduced. The test condition mentioned in the current operating rules described in Tables 3.4(a), 3.4(b), 3.4(c) and "Storage Recovery Principle", i.e. 'Melbourne's storage volume held in Thomson Reservoir' was increased by 50,000 Ml at all levels of operation.

3.5.2.4 Minimum Passing Flows in Yarra River and Thomson River

A considerable amount of water is supplied to Melbourne through the river harvests from Thomson river and Yarra river. The extraction of water from these rivers causes a decrease in downstream flows, which in turn is considered as a cause for deterioration of downstream river health (Department of Sustainability and Environment 2004). Due to this reason, ‘Bulk Water Entitlement Operating Rules’ (Wise Technology Management 1999) and ‘Thomson Bulk Entitlement Order’ (Department of Natural Resources and Environment 2001) specify Minimum Passing Flows (MPFs) - also referred to as environmental flow requirements - for all harvested streams in the Melbourne water supply system. The MPFs for harvested streams in the Melbourne system are given in Table 3.5.

Table 3.5: MPFs for Harvested Streams in Melbourne Water Supply System

Site	MPF (Ml/day)
Yarra river at Warrandyte	245
Yarra river at Milgrove	98
Thomson river below Thomson dam	25 (Mar - Oct) to 75 (Nov-Feb)
Thomson river at Narrows creek	80 (Mar - Oct) to 120 (Nov-Feb)
Thomson river at Coopers creek	150 - 245
Amstrong and Amstrong East creeks weirs combined	5 or natural
McMahons and Micks creeks weirs combined	2 or natural
Starvation and Big Flume creek weirs combined	2 or natural
Maroondah reservoir	1
Correnderrk creek weir	3 or natural
Graceburn creek weir	3 or natural
Donnelly’s creek weir	1 or natural
Silvan reservoir	2 continuous
Cardinia reservoir	5 continuous
O,Shannassy reservoir	4 nominal passing flow
Silver creek weir	Up to 1 depending on the inflow
Wallaby creek weir	Up to 1 depending on the inflow
Toorourrong reservoir	0.2
Tarago river at Scalp creek	5

[Source: 'Melbourne Water REALM Headworks Simulation Model'
(Melbourne Water Corporation 2002c)]

The MPFs given in Table 3.5 are currently being reviewed under a Victorian Government initiative to provide extra water to maintain river health (Department of Sustainability and Environment 2004).

These MPFs are generally maintained through:

- Restricting private diversions and regulating the pumped harvest from Yarra river,
- Regulating the Yarra tributary harvests from Amstrong creek, McMahon creek and Starvation creek, and/or
- Reservoir releases.

Variation in Minimum Passing Flows in Yarra River and Thomson River

- Yarra environmental flow (at Warrandyte) is maintained at current levels
- Environmental flow for Thomson river at Coopers creek is increased from its current levels of approximately 72 Gl/yr (i.e. 150-245 Ml/d) up to 100 Gl/yr

3.5.2.5 Alternative Operating Rules

The four current operating rules and the four variations discussed above were combined together to generate sixteen alternative operating rules for demonstrating the Melbourne system case study in this research. The basis of these sixteen alternative operating rules that were used in REALM simulations to evaluate system performance is summarized below in Table 3.6.

Table 3.6: Alternative Operating Rules Considered in the Case Study

Operating Rule	Demand Restriction Policy	Pumping / treatment at Sugarloaf reservoir	Hydropower generation at Thomson and Cardinia reservoirs	Minimum passing flows in Thomson and Yarra rivers
OPR 1	Current	Current	Current	Current
OPR 2	Current	Current	Current	***Variation***
OPR 3	Current	Current	***Variation***	Current
OPR 4	Current	Current	***Variation***	***Variation***
OPR 5	Current	***Variation***	Current	Current
OPR 6	Current	***Variation***	Current	***Variation***
OPR 7	Current	***Variation***	***Variation***	Current
OPR 8	Current	***Variation***	***Variation***	***Variation***
OPR 9	***Variation***	Current	Current	Current
OPR 10	***Variation***	Current	Current	***Variation***
OPR 11	***Variation***	Current	***Variation***	Current
OPR 12	***Variation***	Current	***Variation***	***Variation***
OPR 13	***Variation***	***Variation***	Current	Current
OPR 14	***Variation***	***Variation***	Current	***Variation***
OPR 15	***Variation***	***Variation***	***Variation***	Current
OPR 16	***Variation***	***Variation***	***Variation***	***Variation***

3.5.3 Melbourne Water REALM Model

Melbourne Water (MW) is currently using REALM for its long-term headworks planning and the calculation of bulk water entitlements. Over the years, the planning decisions related to the Melbourne water supply system, such as drought planning, augmentation planning, evaluating of alternative operating strategies, determining environmental flow volumes etc., relied heavily on the results achievd through the use of the REALM sytem model. However, the overall performance of the model is dependant on the reliability of the input information as well as the model’s capability to represent the actual system operations considering environmental obligations, infrastructure constraints and specific operating rules.

As detailed in ‘Melbourne Water Headworks Simulation Model’ (Melbourne Water Corporation 2002c), the Melbourne REALM model configures the Melbourne water supply system’s harvesting and trasfer system in greater detail. This configuration denotes the bulk water supplies to the three retail water companies, i.e. CWW, SEW and

YVW, through 17 demand nodes. Among the key aspects modelled are all harvesting sites, major reservoirs and transfers, influence of climate on monthly demands, demand restriction rules, environmental flows, pumped harvest from Yarra river into the off-stream Sugarloaf reservoir, operation of hydropower stations downstream of Thomson and Cardinia reservoirs and Winneke treatment plant output. All these system details are bulit into the REALM system file.

The Melbourne transfer system is an interconnected network which supplies the demand zones as well as transfers bulk water from east (where all the major reservoirs are located) to west. Though there are prefered paths for certain major transfers, the actual routes taken depend on seasonal conditions and prevailing hydraulic characteristics. While storage targets and carrier penalties are defined to indicate preferred transfer routes, the model makes use of two more methods for this purpose:

- Regulating transfer capacities using empirical relationships which are a function of the total Melbourne demand at that time, and

- Hardwiring the observed seasonal transfer volumes of some secondary transfers.

The REALM simulations in this study are carried out using the current data used by MW on historic streamflow and climatic records, and future demand forecasts. A higher static demand than the 2002-03 AAD is considered for simulations to account for future demand growth and any adverse streamflow conditions. The relevant REALM input files are supplied by MW to be used in this study. Although the model uses a monthly time-step in simulating the behaviour of the water supply headworks system, it requires the demand forcasts to be input as annual figures, i.e. AAD values, for average climatic conditions (Melbourne Water Corporation 2002c). This study also used the static AAD values in the analysis. The Melbourne model uses monthly disaggregation factors and climatic factors (CLINX) to split the average annual demands into monthly, climatically adjusted demands (Victoria University and Department of Sustainability and Environment 2005).

3.5.4 System Performance Measures (PMs)

As discussed in Section 3.3, the interaction between the various objectives in multi-purpose reservoir operations could be explained by system performance measures, which quantify the characteristics of reservoir system behaviour. Therefore, the selection of objectives as well as the PMs is an important initial stage in this case study.

3.5.4.1 Selection of Objectives

Long-term social, economic, environmental and technical aspects were taken into consideration in specifying the relevant objectives for this case study. Four objectives were derived considering the relevant part of the MW's mission statement related to water supply. The MW mission statement is given below:

> "***Melbourne Water exists to operate a successful commercial business which supplies safe water and removes sewage and stormwater at an acceptable cost and in an environmentally sensitive manner for the benefit of present and future Melbournians***"

The four objectives that were derived from the above statement are:

1. Ensuring a safe and reliable water supply to Melbourne by maximizing the level of service to the water users,
2. Maintaining an acceptable cost for water by minimizing the pumping/treatment costs and maximizing the hydropower revenue,
3. Minimizing the adverse effects on the environment by maximizing the river flows, and
4. Maintaining supply sustainability by maximizing total system storage volume.

3.5.4.2 Identification of PMs

A total of eight PMs that summarizes the system performance under four broad objectives discussed earlier were identified through discussions with resource managers at MW. During the discussions, it was ensured that the chosen set of PMs satisfied the three properties, exhaustiveness, consistency and non-redundancy as explained in Section 3.3. The objectives, the details of the PMs and relevant REALM output files used to compute the PM evaluations are shown in Table 3.7.

Table 3.7: Objectives, Details of the Performance Measures and Output Files for the Case Study

Objective	Performance Measure (PM)	Unit	Minimise or Maximise	Definition	Relevant REALM Output File to compute the PM
Maximize level of service	**PM1** – Monthly supply reliability (SR)	%	Maximise	Percentage of months with no restrictions to the total number of months in the simulation period	REALM log file
	PM2 - Worst restriction level (WL)	-	Minimise	Worst stage of restriction reached during the simulation period	REALM log file
	PM3 - Duration of restrictions (DR)	Months	Minimise	Maximum consecutive duration of any form of restrictions during the simulation period	REALM restriction levels output file
	PM4 - Frequency of restrictions (FR)	-	Minimize	Average annual chance of a restriction event during the simulation period	REALM restriction levels output file
Minimize pumping & treatment costs / Maximize hydropower revenue	**PM5** - Pumping/ treatment costs (PC)	$ mil / year	Minimise	Average annual cost of pumping and treatment during the simulation period*	REALM log file
	PM6 - Hydropower revenue (HR)	$ mil / year	Maximise	Average annual revenue from hydropower generation during the simulation period**	REALM log file
Minimize the effects on environment	**PM7** - River flows (RF)	Gl / year	Maximise	Average annual total river flows during the simulation period***	REALM log file
Maximize supply sustainability	**PM8** - Total system minimum storage (MS)	Gl	Maximise	Minimum monthly total storage volume reached during the simulation period	REALM storage volume output file

Note: * Based on Winneke water @ $60 per Ml (as per discussions with MW officers)
** Based on Thomson and Cardinia hydropower @ $20 per Ml (as per discussions with MW officers)
*** Based on Yarra river downstream of Yering Gorge and Thomson river downstream of Coopers creek

3.5.5 Data Used in the Study

All the data relevant to the Melbourne water supply system, which have been used in this study were supplied by MW. Further to the discussion in Section 3.5.3, the relevant REALM input data files (i.e. streamflow file, demand file and sytem file) of the Melbourne system, containing the input data for MW's 2002-03 planning runs were used in this study. Therefore, it was assumed that the model represented the actual system operations during 2002-03 considering demand restrictions, environmental flow obligations, infrastructure constraints and other specific operational requirements.

3.5.5.1 Streamflow Data

The monthly inflows into the Melbourne system are included in the REALM streamflow input file. Following harvesting sites account for the unregulated inflows to the system in the REALM streamflow file (Melbourne Water Corporation 2002c):

- Maroondah/Sugarloaf system – Graceburn creek, Watts river
- O'Shannassy system – Coranderrk creek, O'Shannassy river
- Thomson/Upper Yarra system – Upper Yarra and Thomson reservoirs
- Upper Yarra tributaries – McMahons and Micks creeks, Starvation and Big Flume creeks, Amstrong and East Amstrong creeks
- Yan Yean system – Plenty river at Toorourrong reservoir, Silver and Wallaby creeks with 3 associated small weirs

The climatic parameters 'Rainfall' and 'Temperature' included in the streamflow file are used to model the evaporation losses from the reservoirs. The Melbourne Water REALM model used for this study, modelled the reservoir evaporation losses only at Greenvale, Yan Yean, Silvan, Cardinia and Sugarloaf reservoirs. At Maroondah, O'Shannassy, Upper Yarra and Thomson reservoirs, the inflows are adjusted accordingly to account for the evaporation losses. As used by MW for its planning studies, a 90-year simulation period was considered with the available historical streamflow sequence of January 1913 - December 2002 and used as future streamflows from January 2005 - December 2094 with individual reservoirs assumed to be 80% full at the start of each simulation period.

3.5.5.2 Demand Data

Further to the general discussion on REALM in Section 3.4, the Melbourne water supply headworks REALM model requires the demand forecasts to be input as the annual figures for average climatic conditions, as usually done for future planning studies. The individual demands for seventeen demand centres are given in the REALM demand input file. The model used the climatic indices 'CLINX' in the streamflow file and the AAD values in the demand file to compute the seasonally adjusted monthly demands for each of these demand centres (Melbourne Water Corporation 2002c). In a particular month, the climatic index is considered to be the same for all the demand centres in the system. Though the AAD for Melbourne in 2002-03 was estimated at 492,000 Ml, the system was simulated for a higher static demand of 556,000 Ml/year in order to account for the future growth and increase in water consumption, and any adverse streamflow conditions etc.

3.5.5.3 System Details

A system file provided by MW, which configures the 2002-03 Melbourne system, was used for the REALM simulations in this study. This system file contains the system configuration described in 3.5.1, the demand restriction rules and reservoir target rules.

System Configuration

Among the key inclusions in the system configuration are all harvesting sites, major reservoirs and transfers, environmental flow obligations, pumped harvest from Yarra river into the off-stream Sugarloaf reservoir, operation of hydropower stations downstream of Thomson and Cardinia reservoirs and WTP output. The necessary adjustments were carried out to the 2002-03 system file in order to depict the variations related to alternative operating rules described in Section 3.5.2.

Demand Restrction Rules

The 2002-03 DRP restriction trigger levels as previously indicated in Table 3.1, provided the basis for the restriction rule curves used in this study. These curves are developed based on system behaviour in the worst historical drought on record and provide for a limited supply under drought conditions (Melbourne Water Corporation 2002b). The restriction entry trigger levels defined in DRP (as total storage volumes) are expressed as percentages of AAD (i.e. 556,000 Ml) for use in the REALM model. The unrestrictable (base) demand was considered as 78% of AAD on the basis of per capita consumption for each winter from 1992-2001 (Melbourne Water Corporation 2002b). The base demand factors, lower rule curve values and upper rule curve values used in the system file, reflecting the 2002-03 DRP are given in Table 3.8.

Table 3.8: REALM Input Restriction Entry Trigger Values

Month	Base Factor (% of AAD)	Lower Rule Curve Value (% of AAD)	Upper Rule Curve Value (% of AAD)
January	6.66	69	166
February	6.02	71	162
March	6.66	74	152
April	6.45	75	148
May	6.66	76	146
June	6.45	77	143
July	6.66	76	146
August	6.66	73	153
September	6.45	71	162
October	6.66	69	166
November	6.45	67	172
December	6.66	68	169

Reservoir Target Rules

The reservoir target volumes were set in the system file according to the underlying preference for distribution of stored water within the system. These general targets are incorporated in the model using separate sets of storage target curves for harvesting and draw-down seasons, draw-down priorities, above-target zones and below-target zones (Melbourne Water Corporation 2002c; Victoria University and Department of Sustainability and Environment 2005) . The general intent of the system storage targets applied to the current operation (Wise Technology Management 1999) is summarised in Table 3.9 and the draw-down priorities included in the system file are as below:

1. O’Shannassy
2. Maroondah
3. Thomson
4. Upper Yarra
5. Sugarloaf
6. Silvan
7. Cardinia
8. Yan Yean
9. Greenvale

Table 3.9: Summary of Reservoir Storage Targets

Storage Reservoir	**Draw-down Season (Dec - Mar)**	**Harvesting Season (Apr - Nov)**
Thomson	Keep high – used as a drought reserve storage	Keep high to maximise harvest in downstream storages and maintain drought reserve
Upper Yarra	Allow to draw down to maximise harvest	Allow to draw down through transfers to Silvan, Cardinia, Greenvale, and Yan Yean to maximise the harvesting potential
O’Shannassy	Small storage – allow to draw down to maximise the harvesting potential	Allow to draw down
Silvan	Keep high to maintain head for efficient transfer	As for draw-down season
Maroondah	Allow to draw down – transfer to Sugarloaf	Allow to draw down - to maximise harvest
Sugarloaf	Keep high – use other sources in preference because of high cost of pumping. Useful as drought reserve and in drought recovery phase	As for draw-down season
Cardinia	Allow to draw down but hold within limited operating range to maintain delivery head	Keep high to maintain delivery head and maximise harvesting potential of upstream storages
Yan Yean	Keep high to maintain hydraulic head for delivery for peak day demand	Need to fill in readiness for seasonal peak
Greenvale	Keep high to maintain hydraulic head for delivery for peak day demand. Use other sources in preference.	Need to fill in readiness for seasonal peak. Use other sources in preference.

(Source: Melbourne Water Corporation 2002c)

3.5.6 Decision Matrix

The PM values calculated from the simulation results for each alternative operating rule are given in Table 3.10 in the form of a decision matrix. To visualize the effects of each PM on the individual operating rules, the ‘Action Profiles’ output window of *Decision Lab 2000* software (Visual Decision 2003) is used. Later in Section 5.3, the features of the *Decision Lab 2000* software, including the ‘Action Profiles’ are explained in detail. In brief, the vertical bars in these profiles represent the rating of an operating rule on a particular PM when all the PMs are considered equally important; upward bars indicate strong performances and downward bars indicate weak performances (Visual Decision 2003).

Table 3.10: Performance Measure Values (Computed from REALM Output Files) for Alternative Operating Rules

	Restriction Policy	Pumping / treatment at Sugarloaf reservoir	Hydropower generation at Thomson and Cardinia reservoirs	Minimum passing flows in Thomson and Yarra rivers	Supply Reliability (%)	Worst Restriction Level	Duration of Restrictions (months)	Frequency of Restrictions	Pumping / Treatment Cost ($mil/year)	Hydropower Revenue ($mil/yaer)	River Flows (Gl/year)	Total System Minimum Storage (Gl)
OPR 1	Current	Current	Current	Current	94.2	2	32	0.022	5.20	5.00	531	745
OPR 2	Current	Current	Current	***Variation***	82.4	4	106	0.044	5.83	5.29	540	468
OPR 3	Current	Current	***Variation***	Current	94.7	2	32	0.022	5.13	4.88	531	783
OPR 4	Current	Current	***Variation***	***Variation***	82.6	4	106	0.044	5.79	5.27	540	469
OPR 5	Current	***Variation***	Current	Current	96.8	1	18	0.022	5.72	5.10	530	770
OPR 6	Current	***Variation***	Current	***Variation***	84.5	4	92	0.033	6.29	5.34	537	505
OPR 7	Current	***Variation***	***Variation***	Current	98.0	1	17	0.022	5.62	4.97	530	822
OPR 8	Current	***Variation***	***Variation***	***Variation***	84.6	4	92	0.033	6.26	5.31	536	510
OPR 9	***Variation***	Current	Current	Current	92.7	2	38	0.033	5.16	4.99	532	763
OPR 10	***Variation***	Current	Current	***Variation***	74.2	5	123	0.078	5.72	5.28	542	526
OPR 11	***Variation***	Current	***Variation***	Current	93.3	2	37	0.033	5.12	4.88	531	802
OPR 12	***Variation***	Current	***Variation***	***Variation***	75.1	5	123	0.078	5.70	5.26	542	526
OPR 13	***Variation***	***Variation***	Current	Current	93.4	2	35	0.033	5.69	5.09	531	789
OPR 14	***Variation***	***Variation***	Current	***Variation***	82.7	4	105	0.044	6.24	5.34	538	564
OPR 15	***Variation***	***Variation***	***Variation***	Current	95.2	2	33	0.022	5.61	4.97	530	835
OPR 16	***Variation***	***Variation***	***Variation***	***Variation***	83.2	4	105	0.044	6.21	5.31	538	565

The 'Action Profiles' suggests that these sixteen operating rules could be loosely categorised into 3 clusters in a very approximate manner, signifying 'High' (i.e. when most number of PMs show above average performance), 'Medium' (i.e. when most number of PMs show average performance) or 'Low' (i.e. when most number of PMs show below average performance) performances as follows:

- 'High' - OPR1, OPR3, OPR5, OPR7 and OPR15
- 'Medium' - OPR6, OPR8, OPR9, OPR11 and OPR13
- 'Low' - OPR2, OPR4, OPR10, OPR12, OPR14 and OPR16

The action profiles of the 'High', 'Medium' and 'Low' performing operating rules are shown in Figures 3.5(a), 3.5(b) and 3.5(c) respectively.

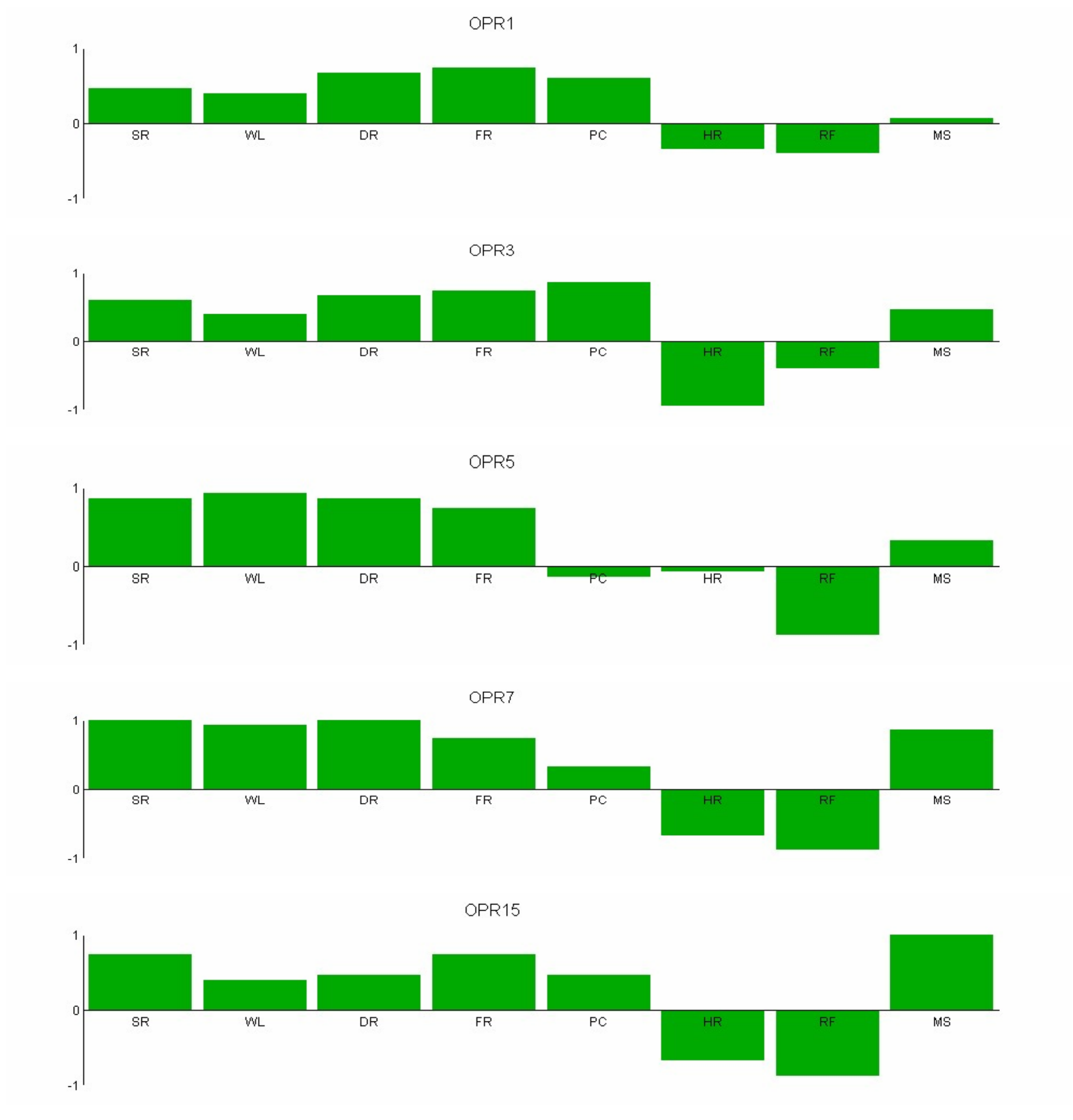

Figure 3.5(a): Action Profiles of 'High' Performing Operating Rules

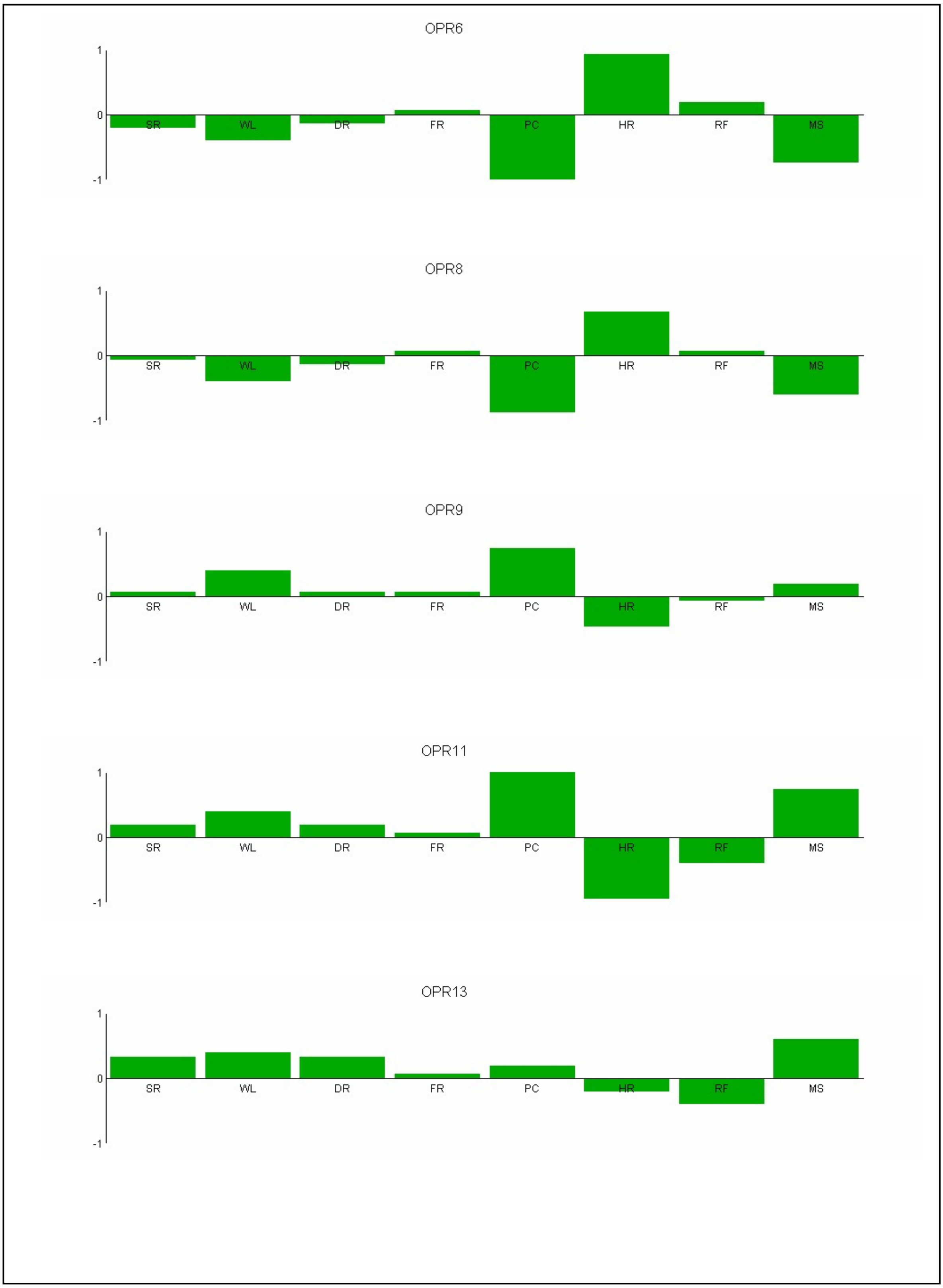

Figure 3.5(b): Action Profiles of ‘Medium’ Performing Operating Rules

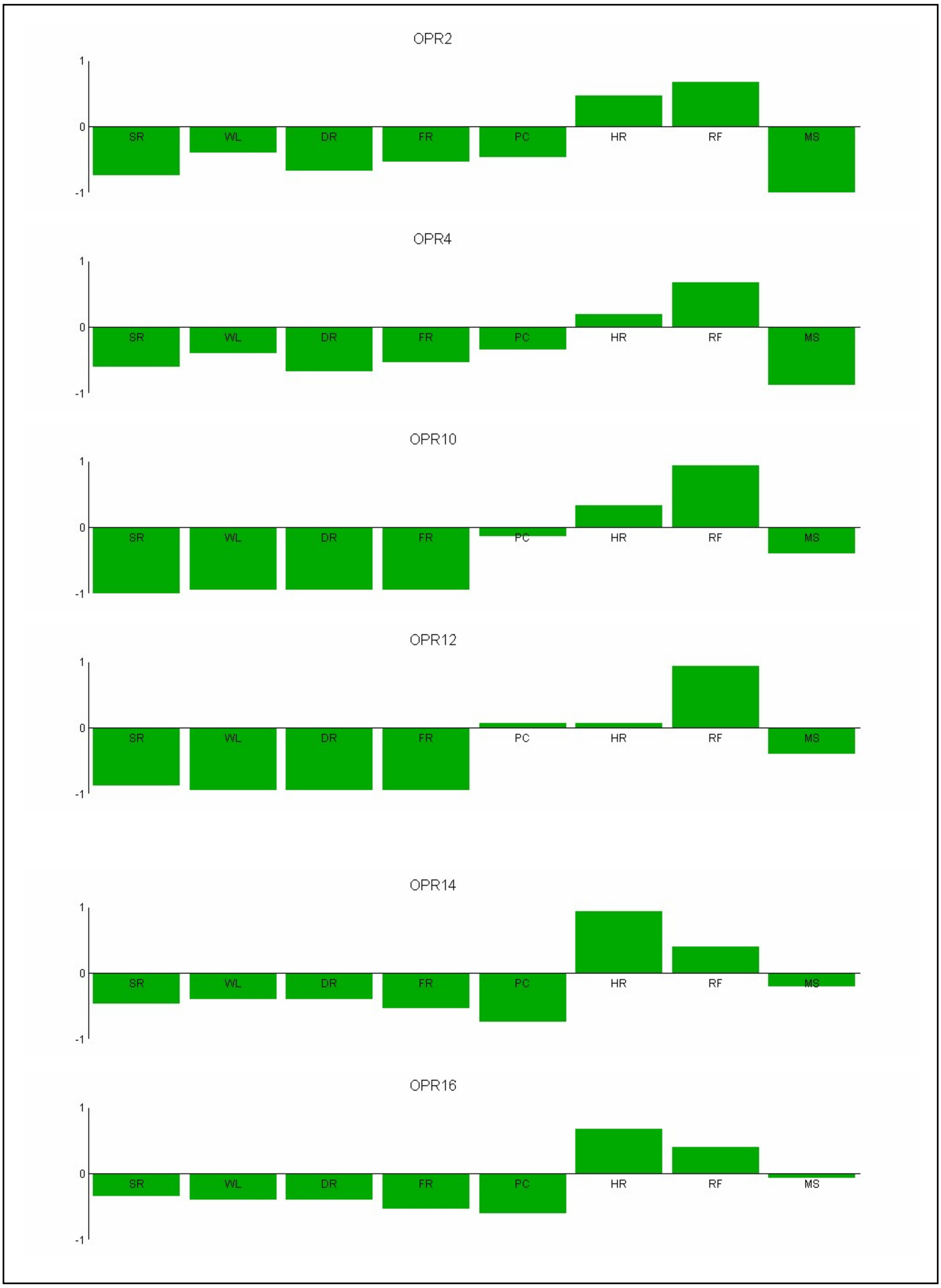

Figure 3.5(c): Action Profiles of ‘Low’ Performing Operating Rules

It is noted that even with an approximate of a ‘High’ performing group of operating rules [Figure 3.5(a)], choosing a single optimum operating rule among them based on rational judgement could be a difficult task to the DM. This problem aggravates when there are many stakeholder representations in a group of DMs with different preference levels on the PMs. It is therefore necessary, in this kind of challenging situations, to aid the DMs with a computer software tool which is capable of assessing all the alternatives, identifying the ‘High’ performing alternatives first and then reaching a consensus among the DMs to arrive at a best compromising operating rule.

3.6 Summary

This chapter described in detail, some past and present practices related to both general and system specific reservoir operations documented in literature, highlighting the use of system simulation models to understand the system behaviour. The operation of multi-purpose, multi-reservoir urban water supply systems with respect to demand restrictions, storage targets and other operating rules were illustrated with particular reference to the REALM headworks simulation model. One of the modern ways of approaching planning and management of complex water resources systems is through systems analysis using simulation models; the identification, analysis and evaluation of the interactions of all the components of the system in space and time. Although the simulation models are considered to be ill-suited in prescribing the best or optimum strategies, when flexibility exists in coordinated system operations, the prescriptive optimisation models offer an expanded capability to systematically select optimal solutions, or families of solutions, under agreed upon objectives and constraints for multi-purpose reservoir systems.

The decision making process related to water supply reservoir operations initiate with an explicit goal agreed upon by the stakeholders, as stated through different categories of objectives and Performance Measures (PMs), followed by the evaluation of alternative operating rules was highlighted in this chapter. The interaction between the various objectives in multi-purpose reservoir operations is explained with a set of system PMs that should satisfy the properties of exhaustiveness, consistency and non-redundancy. The use of qualitative and quantitative PMs in water resources operations is illustrated with some real-world applications. This study used REALM simulations to compute the PMs in the case study. Therefore, the relevant features of the generalised water supply headworks simulation model REALM are also presented.

The Melbourne water supply system case study was introduced with a description of the system features, which existed during 2002-03. The current and alternative operating rules were discussed in relation to four areas of system operations, i.e. demand restrictions policy, pumping/treatment at Sugarloaf reservoir, hydropower generation at Thomson and Cardinia reservoirs and minimum passing flows in Yarra river and Thomson river. Considering the variations to the current operating rules in the above-mentioned areas of system operations, sixteen alternative operating rules were generated for use in the study.

A brief description of Melbourne Water's 2002-03 REALM model was presented. The identification and definitions of four objectives and the eight performance measures is described. The input data used in the simulation process (i.e. streamflow, demand and system data) and the use of REALM model to analyse and compute the PMs on the sixteen pre-defined alternative operating rules was illustrated on the case study. Finally, the results of the PM evaluations on the sixteen alternative operating rules were presented in the form of a decision matrix for use in the decision analysis of alternative operating rules in Chapter 5. Although a loose categorisation of the alternative operating rules was possible with the aid of PM evaluations, choosing a single operating rule based on rational judgement is a difficult task to a DM. Computer software tools capable of analysing this kind of decision problems could provide the DMs with the necessary aid towards reaching the best compromising (optimum) operating rule.

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Chapter 4: Elicitation and Modelling of Stakeholder Preference Parameters

4.1 Introduction

Having demonstrated the manner in which the alternative operating rules could be evaluated through explicitly defined system Performance Measures (PMs) in the previous chapter, it is then necessary to discuss the concept of stakeholder involvement in water supply system operations with particular reference to a sustainable water future. This chapter presents the underlying principles of the stakeholder preference parameter elicitation procedures and the preference elicitation methodology adopted for derivation of the representative stakeholder preference parameters for the Melbourne water supply system case study.

In the context of Multi-Criteria Decision Aiding (MCDA), the term 'preference' usually refers to the desires of the Decision Maker (DM) with respect to either the global preferences on a set of alternatives or to the preference parameters (preference thresholds, weights etc.) related to the individual PMs. In either case, these preferences are considered to be essential elements in real-world decision-making. This study focused on the individual preferences on PMs in terms of preference thresholds and weights.

Brans (2002) points out that the real-world decision-making should essentially consider the personal preferences of the DM to account for his/her freedom and/or the hesitations based on his/her experiences on the subject. Section 2.7.2 described the manner in which the PROMETHEE method takes the subjectivity of the DM into account by way of incorporating these subjective preferences of the DM in the decisions.

Gathering the preference information has always been seen as a difficult and intricate problem leading to uncertainty (Figueira and Roy 2002; Herath 2004). Many experimental studies have confirmed that the DM preferences are highly variable due to various factors and this could lead to bias in the evaluations of the same (e.g. Fischoff

1980; Shapira 1981). For example, the way one presents a question to a person could strongly influence his/her behaviour in expressing the preference (Vincke 1999). Goldstein (1990) and Mousseau (1992) showed that the DM's weights on PMs depend on the type of alternatives presented; weights of PMs changed according to whether the alternatives were chosen from among the best or the worst. In MCDA, 'preference elicitation' refers to the way of assessing DM's desires (or priorities) either on the global preferences on a set of alternatives or with respect to the preference parameters (preference thresholds, weights etc.) related to the individual PMs of the decision problem.

In alternative comparison methods, such as UTA method described in Section 2.4.2, the DM preferences are obtained globally on the set of alternatives itself (e.g. a number of policy decisions). In contrast, the outranking methods such as ELECTRE or PROMETHEE, the DM's preferences are obtained on a set of predefined PMs, which are finally being used to analyse the decision problem. In this study, the preference elicitation process deals with the derivation of preference parameters on the four objectives and the eight PMs defined in Section 3.5.4.

This chapter first highlights the growing popularity of stakeholder participation in the field of natural resources management to achieve its goals towards a sustainable future. Then it examines the nature of stakeholder preference information required in analysing a decision problem using PROMETHEE/*Decision Lab 2000* (Visual Decision 2003), which is applicable to the case study, i.e. input data for PROMETHEE/*Decision Lab 2000*.

Various preference elicitation methods described in literature are also presented in this chapter. Then the interviewer-assisted questionnaire survey methodology adopted for eliciting the required preference information from three major stakeholder groups in the Melbourne water supply system is described. Finally, the survey results are presented explaining the basis for deriving the representative preference parameters of the three stakeholder groups, viz. resource managers, water users and environmental interests groups.

4.2 Stakeholder Participation in Natural Resource Management Decision making

In the past, stakeholder participation in decision-making had been most effective in the areas of environmental, ecosystem and watershed management (e.g. Leach et al. 2002; Pavlikakis and Tsihrintzis 2003). Leach et al. (2002) formalised the concept of a ‘stakeholder partnership’ applied to watershed management, where these consensus-seeking partnerships consist of representatives from private interest groups, local public agencies, and state or federal agencies. They convene as a group regularly, to discuss or negotiate the public policy within a broadly defined issue area. These watershed partnerships are common in United States, Canada and Australia (Leach and Pelky 2001).

Pavlikakis and Tsihrintzis (2003) describe the decision making from human opinion (DeMHO) method which focuses on the quantification of the human opinion, preferences and perceptions towards selecting the most suitable and socially acceptable management plan in protecting or restoring an ecosystem. The method aims at: (a) overcoming the problem of the quantification of the human opinion by consulting (through questionnaire surveys, interviews etc.) the local population of the ecosystem, and (b) involving ‘all interested parties’ in a holistic ecosystem management decision making process with the use of MCDA methods [such as Analytic Hierarchy Process (AHP)] described in Section 2.4.

As previously outlined in Section 2.2, long-term operational decisions of water supply systems are often associated with many objectives, which are not equally recognised and appreciated by all stakeholders. As Curran (1971) points out, a question that had been often asked during the planning process of water resources development projects is, how responsive the water resource manager has been to the public at large, in the broadening of planning objectives beyond economic efficiency to include greater attention to social goals. He further states that the water resources manager, concerned with providing water needs for all its varied uses, is obliged to consider the public interest in his decision making. Curran (1971) also argues that, the public interest, although inferring the superiority of public over purely private interests, is more of a concept of political ethics than an operational objective. Therefore, he suggests that the decision making towards sustainability should combine both the expertise of the water resources manager and the greater public participation.

Loucks and Gladwell (1999) point out that achieving a 'shared' vision of any particular water resource system, its watershed, and its ecosystem is an important step toward reaching decisions that will promote sustainability. Bender and Simonovic (1997) also describe consensus, or in other words the level at which stakeholders are satisfied with the solution to a problem, as a flexible measure of sustainability of water resource systems. According to the ASCE (American Society of Civil Engineers) Task Committee on Sustainability Criteria (1998) and quoted by Loucks and Gladwell (1999), the sustainable water resources systems are:

> *"Water resource systems that are designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity"*

There is a growing shift towards the methodical inclusion of stakeholder preferences in practical decision making situations related to sustainable water resources management (e.g. Ghanbarpour et al. 2005; Herath 2004; Joubert et al. 2003; Leach et al. 2002). Particularly, when the options for increasing water supplies are limited, the existing supplies are becoming exhausted, and with the increasing concerns for preserving the eco-systems, the need for consensus-seeking ways of sustainable management of water resources has become increasingly critical (Galloway 2005; McPhee and Yeh 2004).

In addressing the sustainability issues, the models containing social, economic and environmental impacts as well as hydrologic analysis are widely accepted by the stakeholders (Leach et al. 2002). One such approach was introduced in 1998 when the Water Resources Planning and Management Division of ASCE developed a 'Task Committee on the Use of Shared Vision Modelling in Water Resources Planning' (Palmer 2000). According to Palmer (2000), shared vision models are a natural extension of more traditional water resources planning models; computer models that incorporate planning objectives and performance measures into a framework that allow the generation and evaluation of alternatives in a manner that facilitates conflict resolution.

Labadie (2004) states that the strategy of 'shared vision modelling' is useful for enhancing communication among impacted stakeholders and attaining consensus on planning and operational goals related to water resources systems. Loucks (2000) also discusses the challenges and benefits of applying shared vision modelling to South Florida ecosystem restoration project. It is evident that inclusion of stakeholder preferences in water resources decision-making is becoming a popular approach in addressing the challenges and bringing forward the benefits in terms of a sustainable water future. However an emerging issue is the extent to which stakeholder preferences can be included in the decision modelling process.

Recently, the stakeholder preferences had played a vital role in developing strategies for water resources planning in Melbourne area (Water Resources Strategy Committee 2002b) and in preparing the Victorian government initiatives for sustainable water resources management (Department of Sustainability and Environment 2004).

The operational decisions in water supply may be handled by Decision-Making Group (DMG) s, which could be formed to provide adequate representation from the stakeholder groups. As detailed in Section 2.5, there are numerous decision support software tools, which claim to be able to handle multiple DM situations. Some of these Group Decision Support Software (GDSS) which aid the DMs in evaluating and selecting the best alternatives are (Weistroffer et al. 2005):

- AGAP (**A**id to **G**roups for **A**nalysis and evaluation of **P**rojects) (Costa et al. 2003)
- ARGOS (Colson 2000)
- CTLite (**C**lear**T**hinking **Lite**) (http://www.CTLite.com)
- Decision Lab 2000 (Visual Decision 2003)
- WINGDSS (Csaki et al. 1995)

As described in Section 2.7, the *Decision Lab 2000* software is chosen for the case study, primarily for its user-friendliness and the use of MCDA outranking method

PROMETHEE. Further in this chapter, the preferences of the following three potential key stakeholder groups of the Melbourne water supply system are examined and quantified to be used as input information in *Decision Lab 2000*:

- Resource Managers (RMs),
- Water Users (WUs) and
- Those representing environmental preferences groups (ENs) - simply referred to as 'Environmentalists' in this thesis.

The WUs who represent the residential water users of Melbourne, are meant to use water for various indoor and outdoor purposes. The outdoor uses include watering gardens, filling up of swimming pools, washing vehicles, paved areas and windows etc.

4.3 Stakeholder Preferences for PROMETHEE/*Decision Lab 2000*

It is straightforward to derive the quantitative PM evaluations for different alternatives using predictive simulation models. However, the stakeholder preference parameter evaluations are considered to be more or less subjective in nature and tend to vary for reasons stretching beyond the characteristics of the decision problem. As Pomerol and Barba-Romero (2000) describe, DM's preference evaluations may largely vary on the order in which the PMs are presented to the him/her, the DM's pre-suppositions on the use to which his/her values will be put, any qualitative descriptions used (e.g. a lot, not much, average, good etc.), the precise time when the DM is questioned, etc. Also, in the context of decision aiding, determining the stakeholder preference parameters is considered to be a difficult and tedious process.

Chapter 3 described the manner in which a set of eight PMs was used to summarize the Melbourne water system performance under the (stated) long-term social, economic, environmental and supply sustainability objectives in the case study. To analyse a decision problem using PROMETHEE, it is necessary to have two requirements related to PMs:

(1) Comparison of different PMs independently from their measurement units, and

(2) Definition of priorities of DMs among (relative importance of) the PMs.

The above requirements are met in PROMETHEE/*Decision Lab 2000* by associating two types of input information; a preference function (PF) and a weight to each PM as detailed in Section 2.7.1. In meeting the first requirement, preference functions were derived from the stakeholder responses related to their preference levels on each PM.

In meeting the second requirement as stated above, it is necessary to determine the weights (or relative importance) of PMs. The weights could either be expressed as 'ordinal' or 'cardinal' nature; they are said to be 'ordinal' if only their ranking counts (the largest, second largest etc.) and 'cardinal' if their exact numerical value plays a role (Pomerol and Barba-Romero 2000). As also explained in Chapter 2, according to whether the weights are ordinal or cardinal, they will play different roles in MCDA aggregation methods and the cardinal values are important when the aggregation methods demonstrate an element of compensation. Bouyssou (1986) states that an aggregation method is compensatory when the increase in value of one alternative, relative to one PM, is able to compensate the decrease in the value of the same alternative relative to another PM. However, there are some rare exceptions such as lexicographical methods described in Section 2.3, where only the order of weights is relevant.

With PROMETHEE, the ordinal methods may be employed to elicit DM's preferences on the weights (i.e. relative importance) of PMs, if those ordinal preferences could be interpreted on cardinal scales eventually. However, in contrast to the concept of PF, the concept of weights on PMs was considered to be more comprehensible to the participants.

4.4 Preference Elicitation for MCDA Outranking Methods

As described in Section 2.4.2, the common preference parameters that need to be determined in MCDA outranking methods mainly comprise preference thresholds and weights. However, as later shown in Section 4.3, the format of these preference parameters may vary depending on the input requirements of the MCDA method and the decision support software used in the analysis. For example, PROMETHEE/*Decision Lab 2000* requires PFs and numerical weights on PMs. Therefore, the preference elicitation method should be able to gather the necessary information in the required format to model the stakeholders' preference parameters.

Several methods have been proposed in the literature to derive the weights of the PMs in outranking methods (Figueira and Roy 2002; Hokkanen and Salminen 1994; Mousseau 1995). However, as for eliciting the preference thresholds (e.g. *p*, *q* and *s* in PROMETHEE method), a formalised approach is rarely sighted in the literature. Most of the applications employed the direct method of asking the DMs to prescribe these parameters (e.g. Georgopoulou et al. 1998; Spengler et al. 1998).

Hokkanen and Salminen (1997) used a simple and straightforward method to derive weights in their application of ELECTRE III for choosing a solid waste system. In their study, they requested 45 DMs to scale each PM from 1 to 7, 7 being the most important. They used a second procedure in parallel, where each of these DM was asked to give the numeral '1' to the least important PM, and then deriving the other importance values by thinking how many times more important than the least important one. However, they noted that, when the two sets of weights were normalised, there were only minor differences between the results. Therefore, it could be assumed that the two methods resulted in the same PM weights.

According to Rogers et al. (2000b), a method devised by Mousseau (1995) is the most rigorous in mathematical and psychological terms to obtain the relative weights of PMs. It determines a range of admissible values for the weights, from a set of linear inequalities on these weights. These inequalities are deduced from the responses of the DMs to pairwise comparisons of a set of fictitious options, artificially made-up so that they differ from each other, at most, on three PM evaluations. When the inequalities are solved, a range for each PM weighting, rather than a single weight value, is deduced. The boundary values of the range obtained, in the case of each PM, can be utilised as part of a robustness analysis within MCDA outranking methods and the results compared. However, to overcome the difficulty in handling this complex method manually, DIVAPIME software (Mousseau 1995) was developed in University of Paris (Dauphine).

The method first proposed by Simos (1990) uses a 'Pack of Cards' and a simple procedure, to determine the numerical values for the weights of PMs in an indirect way. Rogers et al. (2000b) describe this 'Simos Procedure' (Figueira and Roy 2002) as follows:

1. A number of cards are handed to the DM, with the name of each PM on a separate card, together with the outline information concerning the nature of the PM. Thus, if *n* cards are handed out, there are *n* PMs in total being considered in the decision problem. A number of blank cards are also supplied.
2. The DM is then asked to order the cards from 1 to *n* in order of importance, with the PM ranked first being the least important and the one ranked last deemed the most important. If certain PMs are in the opinion of the DM, of the same importance (and therefore the same weighting), their cards are grouped together. This physical procedure results in a complete ordering of the *n* PMs.
3. The DM is then asked to consider whether the difference in importance between any two successively ranked PMs (or groups of PMs) should, on reflection, be more or less pronounced. In order to reflect this greater or smaller gap in the weights, he/she is asked to insert any number of blank cards between two successively ranked cards (or groups of cards).

Subsequently, Figueira and Roy (2002), in their 'Revised Simos Procedure' proposed a slight revision to the above 'Simos Procedure' to account for the:

- Information concerning the relationship between the weightings of the most and least important information, and
- Modifications identified as necessary to the weight calculation procedure.

This 'Revised Simos Procedure' gathers the same basic information as the original Simos Procedure, as detailed in (1), (2) and (3) above, together with one additional question, i.e. (4) below:

4. ‘How many times more important the first ranked PM (or group of PMs) is, relative to the last ranked PM (or group of PMs)?’

More details of this method are illustrated with the aid of the case study example in Section 4.5.2.1 (c). A distinct advantage of both the original and revised Simos weighting methods is their ability to express the weighting preferences on an ordinal scale, i.e. the DMs are first asked to indicate an order of importance of the PMs. These ordinal preferences are subsequently converted to numerical weight values to represent the relative importance of PMs.

The respondents often find it easier to express their weightings on an ordinal scale rather than on a numerical scale (Rogers et al. 2000b). The active participation in the procedure also gives the participants an intuitive understanding of the method. Therefore, the stakeholder preference information on PM weights in this case study was collected using the ‘Revised Simos Procedure’.

4.5 Case Study – Stakeholder Preference Elicitation and Modelling for Melbourne Water Supply System

4.5.1 Survey Methodology for Case Study

Numerous methods could be used for collecting the required preference information from stakeholder groups, to derive PFs and weights on PMs. Among these methods, there are mailed questionnaire surveys, telephone interview surveys, personal interview surveys etc. that could be specifically designed for a study. In applying the ‘Revised Simos’ Procedure’ to elicit the importance weights of PMs, this study required the interviewer to meet the each respondent individually. Therefore, a personal interview survey with prepared questions was administered for eliciting all the preference information from the representative stakeholder groups.

In comparison to the ENs and WUs, the RMs were assumed to possess a good knowledge of the system and well conversant with the definitions of the PMs.

Therefore, to derive the PFs, the interviewing procedure and the questionnaire used for accounting and quantifying the preference thresholds from WUs and ENs contained more simplified questions in relation to PFs, whereas a more straightforward approach was used for RMs (as described later). Also, some additional demographic questions were posed to the EN and WU groups in order to understand their identity.

In contrast to the concept of PF, the concept of weights was considered to be more comprehensible to the participants and therefore, to elicit information necessary to derive the numerical weights, a single method, i.e. 'Revised Simos Procedure' (Figueira and Roy 2002), was used across all stakeholder groups (i.e. RMs, WUs and ENs).

With respect to the ethical conduct of research and the use of human subjects in questionnaire interview surveys, any research conducted by Victoria University (VU) was required to comply with the guidelines released by the Australian Vice-Chancellors' Committee (AVCC), the Australian Research Council (ARC), and the National Health and Medical Research Council (NHMRC). Therefore, the VU Ethics Committee clearance, which endorses the above guidelines, was obtained for the questionnaire interview procedure, prior to posing it to the survey participants.

The interview procedure for ENs and WUs was pilot-tested first, with eight staff members from VU where the respondents were also given an opportunity to comment on the questionnaire in general. The questionnaire used for the pilot survey is given in Appendix D. Based on the feedback from the pilot survey, some minor adjustments and refinements were made to the pilot questionnaire and the interview procedure (Appendix D), before the full survey was carried out. The RM survey questionnaire and the information provided to the RMs prior to the interview are given in Appendices E1 and E2 respectively. The same survey questionnaire was used for the ENs and WUs and it is given in Appendix F. However, Q3 and Q4 (of Appendix F) of the questionnaire were only specific to WUs, therefore ENs were not required to answer these questions.

The personal interview survey was conducted on a total of 97 personnel from Melbourne Water (MW) and VU, representing the three stakeholder groups. Six (6) staff members of the Water Resources Group at MW represented the RMs, while six (6) academic staff members/post-graduate students who are working on environmental sustainability matters at VU represented the ENs. Other eighty-five (85) staff members from two faculties of VU represented the WUs.

A personalised e-mail was sent to 154 staff members of VU representing the WUs, inviting them to participate in the survey as residential water users. Initially there was only a 27% response rate but a follow-up telephone call raised this involvement to 55%. Consequently, 85 water users (or residential consumers) were recruited to participate in the survey. Although this WU group may be considered as a selective sample, the nature of the research meant that it was sufficient for the purpose and was within time and cost limitations. It should also be noted that these surveys were conducted during the period April - September 2004, when Melbourne was undergoing Stage 2 water restrictions as per the 2002-03 Drought Response Plan (DRP).

For purpose of this study, an overall goal for the operation of the Melbourne water supply system was developed considering the MW's mission statement, which is given in Section 3.5.4.1. The adopted goal for this study is:

> **'To ensure a safe and reliable water supply at an acceptable cost and in an environmentally sensitive manner for the benefit of the present and future Melbournians'**

Since the above overall goal is considered to address the water supply system operations in four different perspectives, i.e. social, economic, environmental and supply sustainability, in a very broad sense, the total or partial agreement with this goal by the participants was considered to be central for the optimisation of the objectives in this study, and hence it was included in the questionnaire.

4.5.1.1 Survey Methodology and Responses - RMs

As stated earlier, the RMs' questionnaire interview survey was conducted on six resource managers from MW.

(a) Preference Functions on PMs for RMs

As described earlier, the relative preference of one potential alternative to another with respect to a particular PM could be expressed by a PF. From each respondent, it was aimed to identify a PF for each PM. Since the RMs, who are the employees of MW, were assumed to be well conversant with the definitions of PMs and their feasible range of values within the statutory requirements, deriving these PFs for resource managers was considered to be quite straightforward.

The RMs were required to answer a basic survey questionnaire (Appendix E1) to directly determine the PFs. To assist them with the definitions of various parameters described in the questionnaire, an information attachment was also provided (Appendix E2) to the RMs prior to the interviews. This attachment provided the written explanations on the PFs, i.e. the six different types of generalised PF types and the precise meanings of the preference thresholds (*p, q* & *s*). At the interview, they were asked to select a PF type for each of the eight PMs. Most RMs wished to use the direct method of selecting a PF for each of the PMs from the six available types of generalised PFs. However, in cases where the RMs were not comfortable with all six types of PFs, they were allowed to select from Type V and its variants (Types I, II and III).

First, the RMs select the PF type (Figure E2-3 in Appendix E2) and then expressed a maximum difference in PM value that they would like to ignore till they do not feel a difference in between two alternative operating rules (this gave the value for '*q*'). Then they were given the opportunity to express a difference in PM value beyond which they feel one alternative is definitely preferred over the other (this gave the value for '*p*') in terms of this PM. The shape of the curve they chose along with the corresponding values of '*p*' and '*q*' or '*s*' defined the preference function for each of the PM. The details of the PF types chosen by the six RMs are presented in Section 4.5.2.1.

(b) Weights on PMs for RMs

As detailed in Table 3.7, there were eight PMs under four objectives specified for the case study. It was noted that the number of PMs considered under each objective was different; for example, there were four PMs under the objective 'maximising the level of service' whereas only one PM was considered under 'minimising the effects on the environment'. Pomerol and Barba-Romero (2000) state that these unequal number of PMs considered under the objectives could, in some cases, result in overweighting certain objectives, but no method has been proposed by them to overcome this problem.

To avoid the tendencies of overweighting or underweighting any objective in the current case study example, in concept earlier proposed by Kodikara et al. (2005) two separate weight sets were first calculated for PMs and objectives for each respondent. The initial PM weights thus calculated are referred to as the 'intermediate weights of PMs' in this thesis. Out of these two weight sets, it was assumed that he/she would have priority to address the importance of objectives. Therefore, a correction factor (referred to as 'objective weight factor' in this thesis) was applied to the intermediate weights of PMs based on the objective weights and the total aggregated PM weights in the corresponding objective category.

The final weights of PMs were then calculated by multiplying the 'intermediate weight' of the PM with the 'objective weight factor'. A similar approach was also promoted by Abrishamchi et al. (2005). Briefly, the procedure adopted in the current case study example comprised three steps, which are demonstrated on the RM1's responses in Section 4.5.2.1:

Step (1) - Determine an intermediate weight for each PM reflecting the relative importance among PM within each objective.

Step (2) - Determine the weight of each objective, reflecting the relative importance among the objectives.

Step (3) - Compute the final PM weight by multiplying the normalised intermediate PM weight by the corresponding objective weight factor.

In step (1) and step (2) above, both normalised values of the intermediate weights of PMs and the objective weights are calculated using the information elicited through the 'Revised Simos Procedure' (Figueira and Roy 2002) explained in Section 4.4.

This study engaged three sets of cards for the survey, containing the labels of PMs, the labels of objectives, and some blanks as shown in Figure 4.2.

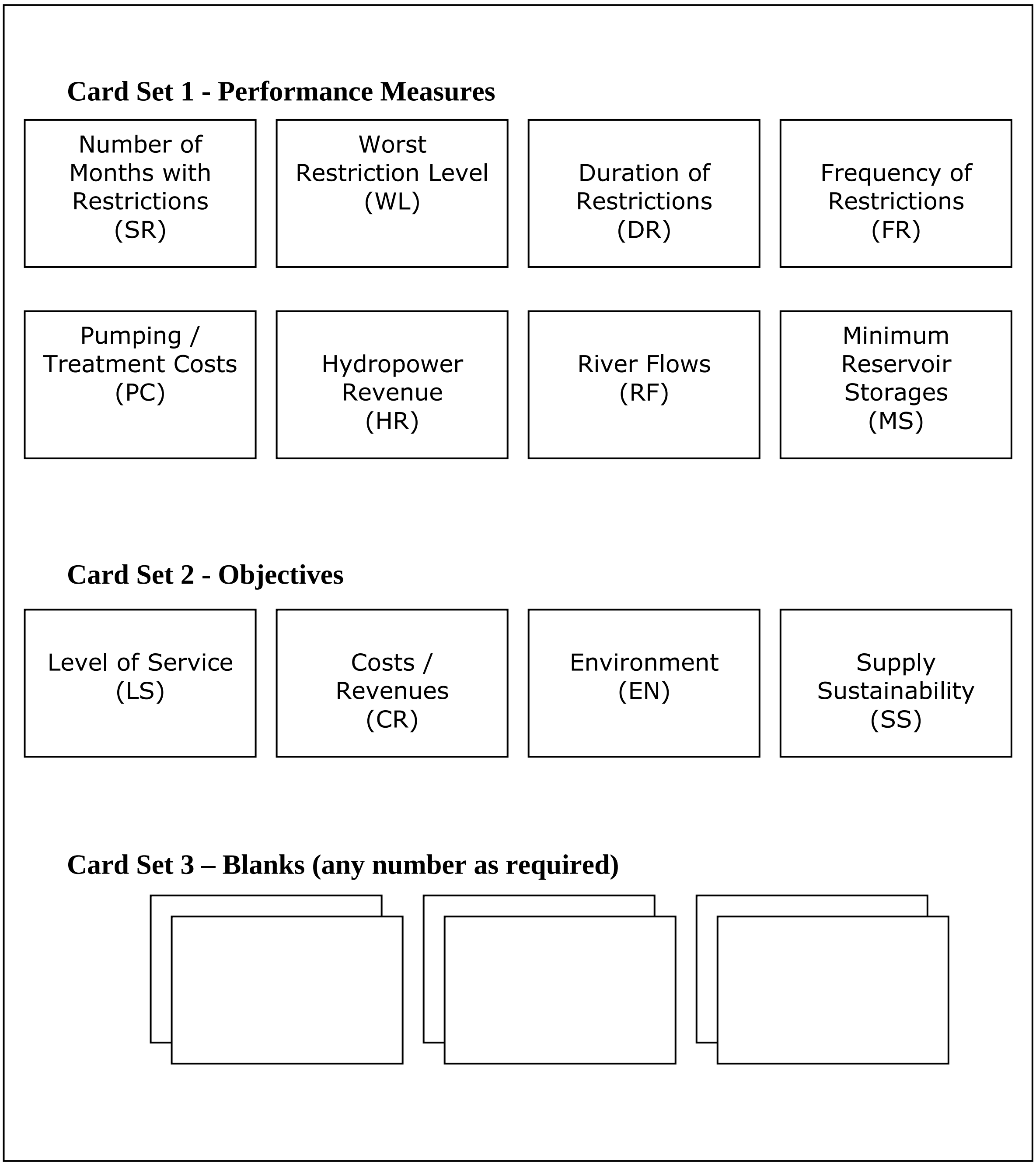

Figure 4.2: Three Sets of Cards used in the Questionnaire Survey

The first set of cards (8 cards) carried a name of a PM on each of the cards, the second set (4 cards) carried a description of an objective on each of the cards and the third set contained some blank cards (any number as required). The steps (1), (2), (3), and (4) detailed earlier in Section 4.4 were followed by the participants for PMs first (with card sets 1 and 3), and then the procedure was repeated for the objectives (with card sets 2 and 3). The complete survey responses to the RM questionnaire (Appendix E1) are given in Appendix G1.

4.5.1.2 Survey Methodology and Responses – WUs and ENs

(a) Preference Functions for WUs and ENs

The WUs and ENs were assumed to be less familiar with the various statutory requirements on the operation of the water supply system and to have only a limited knowledge on the actual operating levels of certain PMs (e.g. PM5 - Pumping/treatment costs, PM6 - Hydropower revenue and PM7 - River flows). Particularly, the concept of PF was not considered to be readily understood by them. Under these circumstances, the practicality of deriving PFs by the direct method as was done with the RMs was questionable. Therefore, for WUs and ENs, the interviewer was assisted with a structured questionnaire with necessary information. The responses received were then used to derive the required PFs on PMs in an indirect way.

In preparing the questionnaire for these two stakeholder groups, a Type IV curve was assumed to model the PFs for PM2 – Worst restriction level, due to PM2 having a logical step-like function lending itself to a Type IV curve function. A Type V curve was assumed to model the PFs for all other PMs, since Types I, II and III can be considered as a subset of Type V and also the preferences of most PMs can be represented by a Type V curve.

The next step in preparing the questionnaire was to determine the ‘*p*’ and ‘*q*’ parameters for each of the PMs. 5-point quantitative scales defined the feasible ranges of PMs, which are familiar to the participants [i.e. PM1 - Monthly reliability of supply (SR), PM2 - Worst restriction level (WL), PM3 - Duration of restrictions (DR), PM4 - Frequency of restrictions (FR) and PM8 - Total system minimum storage (MS)]. 5-point qualitative scales defined the feasible ranges of all other PMs [i.e. PM5 - Pumping / treatment costs (PC), PM6 - Hydropower revenue (HR) and PM7 - River flows (RF)].

The qualitative scales also included a familiar base value, e.g. the 'minimal pumping' (current amount of pumping) for PM5, to make it easier to understand and express the preference levels. The details of the scales used for WUs and ENs survey are given in Table 4.1.

In deriving the '*p*' and '*q*' parameters from the responses, the various preference levels indicated by the 5-point qualitative scales (for PM5, PM6 and PM7) were fitted within the feasible range (in equal intervals) of the corresponding PM and representative numerical values were assigned to each preference level, taking the base value as a reference point. In quantitative scales (for PM1, PM2, PM3, PM4 and PM8), the representative value was simply considered as either the corresponding middle value within the range or the scale value itself (if there is one), for each preference level. These representative values corresponding to various preference levels in the feasible ranges for all eight PMs are also given in Table 4.1.

WUs and ENs were also given the opportunity to indicate whether they wish to leave the decisions with the authorities on matters related to pumping / treatment costs, hydropower generation, river flows and total system minimum storage. This option was useful in cases where the participants were uncertain about the optimum levels of operation related to those PMs due to any unperceived conflicts among them. The option of ticking the 'As necessary' box in Q12, Q13, Q14 and Q15 of the WUs and ENs survey questionnaire (Appendix F) facilitated this.

Table 4.1: Various Properties, Feasible Ranges and Scales of PMs used for Survey with Water Users / Environmentalists

Description	Supply Reliability (SR)	Worst Restriction Level (WL)	Duration of Restrictions (DR)	Frequency of Restrictions (FR)	Pumping / Treatment Costs (PC)	Hydropower Revenue (HR)	River Flows (RF)	Total System Minimum Storage (MS)
Min. /Max. Property	Max.	Min.	Min.	Min.	Min.	Max.	Max.	Max.
Type	Quantitative	Qualitative	Quantitative	Quantitative	Quantitative	Quantitative	Quantitative	Quantitative
Type in the Questionnaire	Quantitative	Qualitative	Quantitative	Quantitative	Qualitative**	Qualitative**	Qualitative**	Quantitative
Feasible Range*	0 - 100	0 - 4	0 - indefinite	0 - 1	2.0 - 8.0	0 - 5.4	0 - 320	0 - 1773
Feasible Operating Range	95 - 100	0 - 3	0 - 12	0 - 1	0 - 8.0	2.85 - 5.4	160 - 240	611 - 700
Unit	%		months		$mil / year	$mil / year	Gl / year	Gl
Base Value***					Minimal P&T costs, 2 $mil/yr	Minimal HP revenue, 2.85 $mil/yr	Minimum env. flow releases, 160 Gl /yr	
Values / value intervals in the Questionnaire	More than 90 % 90 - 75 % 75 - 50 % 50 - 25 % Less Than 25 %	0 1 2 3 4	3 months or less 6 months 12 months 24 months 36 months or more	Zero Once in 10 yrs Once in 5yrs Once in 3yrs Once per year or more	No pumping Minimal Pumping Small Amounts Moderate Amounts Large Amounts	Large Amounts Moderate Amounts Small Amounts Minimal Amounts No Hydropower	High Flows Moderate Flows Minimum Requirements Less than Minimum Requirements No releases	More than 95 % full 65 % full 50 % full 30 % full Less than 30 % full
Value representing the interval	95 82.5 62.5 37.5 12.5	0 1 2 3 4	3 6 12 24 120	0.00 0.10 0.20 0.33 1.00	0.00 2.00 4.00 6.00 8.00	5.40 4.55 3.70 2.85 0.00	320 240 160 80 0	1596 (97.5%) 1152 (65%) 887 (50%) 532 (30%) 266 (15%)

Notes:

* Without considering any operational constraints or statutory requirements.

** Preference levels are expressed on a qualitative scale since the quantitative values provide less meaning to the Water Users or the Environmentalists. This scale also included a familiar base value to make it easier to express the preferences.

*** On the qualitative scales of PC, HR and RF, the preference levels are defined with respect to the base value.

During the survey, the participants were requested to express their preference levels (by ticking two boxes) i.e. ‘Acceptable’ and ‘Strictly not beyond’ on each of the PMs. A typical answer received during the questionnaire survey on the preference levels of PM1 - Monthly supply reliability (with a quantitative scale) and PM5 - Pumping/treatment cost (with a qualitative scale) are presented in Figure 4.3 and Figure 4.4 respectively.

	Acceptable	***Strictly not beyond***
More than 90%		
90% - 75%	√	
75% - 50%		
50% - 25%		√
Less than 25%		

Figure 4.3: Typical Preference Levels of PM1– Monthly Supply Reliability (SR)

	Acceptable	***Strictly not beyond***
No pumping		
Minimal pumping		
Small amounts	√	
Moderate amounts		√
Large amounts		

Figure 4.4: Typical Preference Levels of PM5 - Pumping / Treatment Costs (PC)

Having received the responses from WUs and ENs for all eight PMs and subsequently converting their preference levels to numerical values, it was possible to use this information to determine ‘*q*’ and ‘*p*’ values for each PM and for each participant.

The most desired end of the preference scale for each of the PMs are given in Table 4.2. The value ‘*q*’ was derived as the difference between the most desired end of the preference scale (which has already been established) and the ‘Acceptable’ level (as indicated by the respondent).

Table 4.2: Most desired End of the Preference Scale for Each PM

Performance Measure (PM)	Most Desired End of the Preference Scale
PM1 – Monthly Supply Reliability (SR)	100%
PM2 – Worst Restriction Level (WL)	0
PM3 – Duration of Restrictions (DR)	0 months
PM4 – Frequency of Restrictions (FR)	0
PM5 – Pumping / Treatment Costs (PC)	0
PM6 – Hydropower Revenue (HR)	5.4 $mil / Year
PM7 – River Flows (RF)	320 Gl / year
PM8 – Total System Minimum Storage (MS)	1773 Gl

Similarly, '*p*' is derived as the difference between the most desired end of the preference scale and 'strictly not beyond' level (as indicated by the respondent). For PM1, the most desired end of the scale is 100%. Therefore, according to Table 4.1 and Figure 4.3, '*q*' = 100% - 82.5% = 17.5% and '*p*'= 100% - 37.5% = 62.5%. For PM5, the most desired end of the scale was 'No pumping' with its representative value of 0, and therefore, $q = (4.0\text{-}0.0) = 4.0$ and $p = (6.0\text{-}0.0) = 6.0$ (Table 4.1 and Figure 4.4). The '*q*' and '*p*' values thus derived for all the participants (85 WUs and 6 ENs) are given in Sections 4.5.2.2(b) and 4.5.2.3(b) respectively.

(b) Weights for WUs and ENs

The information necessary for determining the weights for WUs and ENs were obtained using the same procedure adopted for the RMs as described in Section 4.5.1.1 (b). The complete survey responses for the WU and EN questionnaire (Appendix F) as recorded for 85 WUs and 6 ENs are given in Appendices G2 and G3 respectively.

4.5.2 Survey Results – Preference Functions, Weights and Other Details

The responses recorded during the questionnaire survey were mainly used to derive the PFs and the required weights of PMs for the analysis of alternative operating rules. However, there were some additional information gathered during the survey, such as, the extent of agreement with the overall goal (for all the participants) and some demographic details (this is only for WUs), which are presented below.

4.5.2.1 Survey Results with RMs

(a) Agreement with the Overall Goal

In responding to the Q1 of the RM questionnaire (Appendix E1), all the RMs were in total agreement with the overall goal.

(b) Preference Functions – RMs

The PF types derived from the RMs responses to the questionnaire are shown in Table 4.3.

Table 4.3: Preference Functions on PMs – Resource Managers

Resource Manager	Performance Measure (PM)							
	SR	WL	DR	FR	PC	HR	RF	MS
RM1	Type I	Type I	Type V	Type V	Type V	Type V	Type I	Type III
			$q = 4$	$q = 0.06$	$q = 1$	$q = 0.15$		$p = 90$
			$p = 8$	$p = 0.1$	$p = 2$	$p = 2.15$		
RM2	Type II	Type VI	Type II	Type II	Type II	Type II	Type I	Type V
	$q = 2$	$s = 2$	$q = 6$	$q = 0.067$	$q = 3$	$q = 1$		$q = 270$
								$p = 450$
RM3	Type III	Type III	Type III	Type V	Type V	Type III	Type III	Type IV
	$p = 5$	$p = 3$	$p = 12$	$p = 0.2$	$q = 1$	$p = 3.6$	$p = 80$	$q = 92$
				$q = 0.1$	$p = 5$			$p = 184$
RM4	Type II	Type II	Type II	Type V	Type V	Type V	Type III	Type III
	$q = 5$	$q = 3$	$q = 10$	$p = 0.2$	$q = 2$	$q = 0.2$	$p = 80$	$p = 50$
				$q = 0.05$	$p = 6$	$p = 3.2$		
RM5	Type II	Type II	Type II	Type II	Type I	Type II	Type II	Type II
	$q = 5$	$q = 2$	$q = 12$	$q = 0.2$		$q = 1.9$	$q = 80$	$q = 39$
RM6	Type II	Type II	Type II	Type II	Type II	Type II	Type II	Type I
	$q = 5$	$q = 3$	$q = 12$	$q = 0.06$	$q = 2$	$q = 1.9$	$q = 30$	

(c) Weights – RMs

As stated earlier, the intermediate weights for PMs and objectives are calculated using the Revised Simos Procedure by Figueira and Roy (2002) described in Section 4.4. These intermediate weights of the PMs are then multiplied by the corresponding objective weight factor to calculate the final PM weights. In order to illustrate the method on a sample calculation, RM1's responses on PMs, which are given in Figure 4.5 below, is used.

Step (1) - Calculation of the Intermediate Weights of PMs

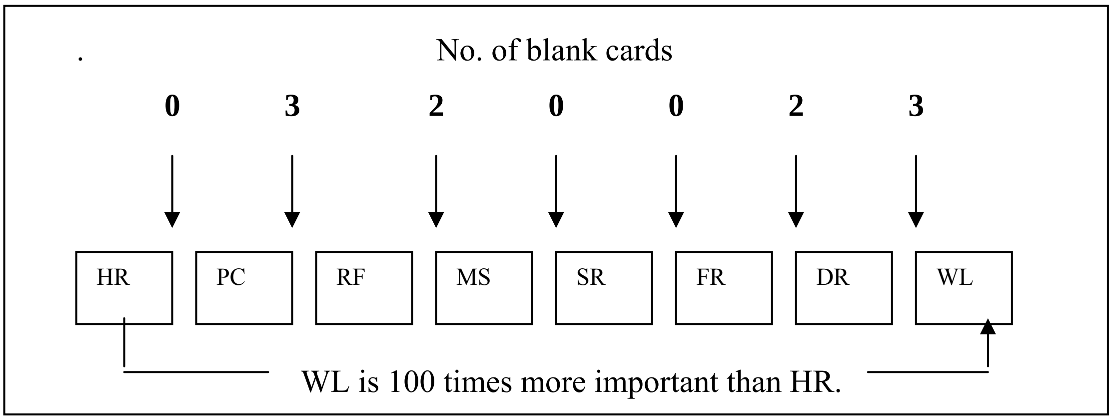

Figure 4.5: RM1's Responses on PM Cards

The rank (*r*) of a PM is defined in the order of increasing importance. 'z' is a parameter defined by the responses to Q2 of RM questionnaire - Appendix E1 (e.g. RM1's 'WL is 100 times important than HR'). In this case: z = 100 (Figure 4.5).

When there are no blank cards placed in between two PM cards, it is taken, as one gap existing between them. Likewise, if there are three blank cards placed in between two PMs, there are four gaps in between them. If X is the total number of gaps between highest ranked PM and the lowest ranked PM (i.e. WL and HR for RM1), then parameter u, such that u = (z-1)/X, is defined to calculate the non-normalised weights of PMs. It is noted that each gap will contribute a weight value equal to 'u' to the next highest rank.

Therefore for RM1, z = 100 and

Total number of gaps between highest and lowest ranked PMs, X = 17 (Table 4.4)

Then, u = (z-1)/X = (100-1)/17 = 5.824

From this, the non-normalised weight $k(1),\ldots,\ k(r),\ldots,\ k(\bar{n})$ associated with each class of equally placed PMs, arranged in order of increasing importance is calculated for $r = 1,\ldots,\ \bar{n}$ where $\bar{n}$ = number of ranking levels as:

$$k(r) = 1 + u(x_{o+}\ \ldots\ldots\ x_{r-1}) \text{ with } x_o = 0$$

If there are a number of equally place PMs on rank r, all the PMs are given the same non-normalised weight $k(r)$. The final intermediate weights of PMs thus derived from RM1's responses are given in Table 4.4.

Table 4.4: Sample Calculation using 'Revised Simos Procedure' to Derive Intermediate Weights of PMs on RM1's Responses

*Rank, *r*	*PMs in the rank *r*	Number of PMs in rank *r*	*Number of blank cards following rank *r*, *w*	No. of gaps between *r* and (*r*+1), x_r	Non-normalized Intermediate weight, *k(r)*	Total	Normalized weight	Intermediate Weight
1	***HR***	1	***0***	1	1	1.00	0.26675	0
2	***PC***	1	***3***	4	6.823529	6.82	1.820179	2
3	***RF***	1	***2***	3	30.11765	30.12	8.033893	8
4	***MS***	1	***0***	1	47.58824	47.59	12.69418	13
5	***SR***	1	***0***	1	53.41176	53.41	14.24761	14
6	***FR***	1	***2***	3	59.23529	59.24	15.80104	16
7	***DR***	1	***3***	4	76.70588	76.71	20.46132	20
8	***WL***	1	_	_	100	100.00	26.67504	27
			Sum	17		374.882	100	100

Note: *RM1's responses recorded at the interview survey are indicated in bold

The ranks (or the level of importance) assigned by the RMs for each PM and the resultant intermediate weights of PMs within each objective computed using the 'Revised Simos Procedure' is given in Table 4.5.

Table 4.5: Ranks and Intermediate Weights of PMs - Resource Managers

Resource Manger		Objective / Performance Measures (PM)							
		Level of Service				Cost / Revenue		Environment	Supply Sustainability
		SR	**WL**	**DR**	**FR**	**PC**	**HR**	**RF**	**MS**
RM 1	Rank	5	8	7	6	2	1	3	4
	Weight	**14**	**27**	**20**	**16**	**2**	**0**	**8**	**13**
RM 2	Rank	2	5	5	2	2	1	8	5
	Weight	**12**	**13**	**13**	**12**	**12**	**10**	**15**	**13**
RM 3	Rank	4	7	3	5	2	1	6	8
	Weight	**12**	**21**	**7**	**14**	**3**	**0**	**17**	**26**
RM 4	Rank	2	6	1	7	4	3	5	8
	Weight	**7**	**16**	**6**	**19**	**9**	**8**	**13**	**22**
RM 5	Rank	6	8	7	5	4	2	1	3
	Weight	**18**	**24**	**20**	**15**	**11**	**5**	**0**	**7**
RM 6	Rank	6	3	5	4	2	1	7	7
	Weight	**16**	**8**	**15**	**12**	**4**	**1**	**21**	**21**

Step (2) – Calculation of the Objective Weights

In Similar calculation procedure, the ranks assigned by the RMs for each objective and the resultant objective weights (normalised) were computed using the revised Simo's procedure. The objective weights thus calculated are shown bold in Table 4.6.

Table 4.6: Ranks and Objective Weights of PMs - Resource Managers

Resource Manager		Objectives			
		Level of Service	Cost / Revenue	Environment	Supply Sustainability
RM 1	Rank	4	2	1	3
	Weight	**50**	**17**	**0**	**33**
RM 2	Rank	4	2	3	1
	Weight	**30**	**23**	**27**	**20**
RM 3	Rank	3	1	3	4
	Weight	**20**	**1**	**20**	**58**
RM 4	Rank	1	2	3	4
	Weight	**11**	**19**	**27**	**43**
RM 5	Rank	4	3	1	2
	Weight	**45**	**36**	**0**	**18**
RM 6	Rank	2	1	3	3
	Weight	**23**	**2**	**37.5**	**37.5**

Step (3) – Calculation of Final PM Weights

As stated earlier, to compute the final weight of the PMs, addressing the priority consideration on the four objectives according to the ranks indicated, the normalised intermediate weights derived for the PMs (as given in Table 4.5) were multiplied by an ‘Objective Weight Factor’ defined as:

$$\text{Objective Weight Factor} = \frac{\text{Total aggregated intermediate PM weights in the objective}}{\text{Corresponding objective weight}}$$

For example, the four PMs: SR, WL, DR and FR, all belong to ‘Level of Service’ objective. RM1’s intermediate weights for SR, WL, DR and FR are 14, 27, 20, and 16 respectively (Table 4.5).

Total aggregated intermediate PM weights within the ‘Level of Service’ objective is (14+27+20+16) = 77, and the corresponding objective weight for ‘Level of Service’ = 50 (Table 4.6). Therefore,

Objective Weight Factor for ‘Level of Service’ = 50/77 = 0.649, and
RM1’s intermediate weight of SR = 14 (Table 4.5).
Therefore, RM1’s final weight for SR = 14 x 0.649 = 9.09

The final (rounded) PM weight sets thus calculated for RMs are shown bold in Table 4.7. These final weight values ensured that RMs’ priority preferences on objectives were accounted for in the final decision. The final weight values of PMs (Table 4.7) were considered as the input weight parameters for the individual RM in the analysis.

4.5.2.2 Survey Results with WUs

The WU questionnaire survey responses were recorded for eighty-five residential water users from VU. The results were recorded in three categories below:

- Demographic details and the agreement with the overall goal of the participants
- Preference functions and
- Weights

Table 4.7: Final (Rounded) Weights of PMs – Resource Managers

Objective	Performance Measure (PM)	Resource Manager																							
		RM 1				**RM 2**				**RM 3**				**RM 4**				**RM 5**				**RM 6**			
		Intermediate Weight on PM	Objective Weight	Final Weight	**Final Rounded Weight**	Intermediate Weight on PM	Objective Weight	Final Weight	**Final Rounded Weight**	Intermediate Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Intermediate Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Intermediate Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Intermediate Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**
LS*	**SR**	14	50	9.09	**9**	11.7	30	7.02	**7**	12	20	4.444	**4**	7	11	1.604	**2**	18	45	10.52	**11**	18	23	7.811	**8**
	WL	27	50	17.53	**18**	13.3	30	7.98	**8**	21	20	7.778	**8**	16	11	3.667	**4**	24	45	14.03	**14**	8	23	3.472	**3**
	DR	20	50	12.99	**13**	13.3	30	7.98	**8**	7	20	2.593	**3**	6	11	1.375	**1**	20	45	11.69	**12**	15	23	6.509	**7**
	FR	16	50	10.39	**10**	11.7	30	7.02	**7**	14	20	5.185	**5**	19	11	4.354	**4**	15	45	8.766	**9**	12	23	5.208	**5**
Sub Total		77		50		50		30		54		20		48		11		77		45		53		23	
CR*	**PC**	2	17	17	**17**	11.7	23	12.4	**12**	3	1	1	**1**	9	19	10.06	**10**	11	36	24.75	**25**	4	2	1.6	**2**
	HR	0	17	0	**0**	10	23	10.6	**11**	0	1	0	**0**	8	19	8.941	**9**	5	36	11.25	**11**	1	2	0.4	**0**
Sub Total		2		17		21.7		23		3		1		17		19		16		36		5		2	
E*	**RF**	8	0	0	**0**	15	27	27	**27**	17	20	20	**20**	13	27	27	**27**	0	0	0	**0**	21	37.5	37.5	**38**
Sub Total		8		0		15		27		17		20		13		27		0		0		21		37.5	
SS*	**MS**	13	33	33	**33**	13.3	20	20	**20**	26	58	58	**58**	22	43	43	**43**	7	18	18	**18**	21	37.5	37.5	**38**
Sub Total		13		33	**33**	13.3		20		26		58		22		43		7		18		21		37.5	
			SUM	100	100			100	100			99	99			100	100			99	100			100	101

Note:

LS* = Level of Service, CR* = Costs and Revenue, E* = Environment, SS* = Supply Sustainability

(a) Demographic details and the Agreement with the Overall Goal – WUs

***Age** (Responses to the Q1 of the questionnaire)*

The age distribution of surveyed residential WUs is described in Figure 4.6.

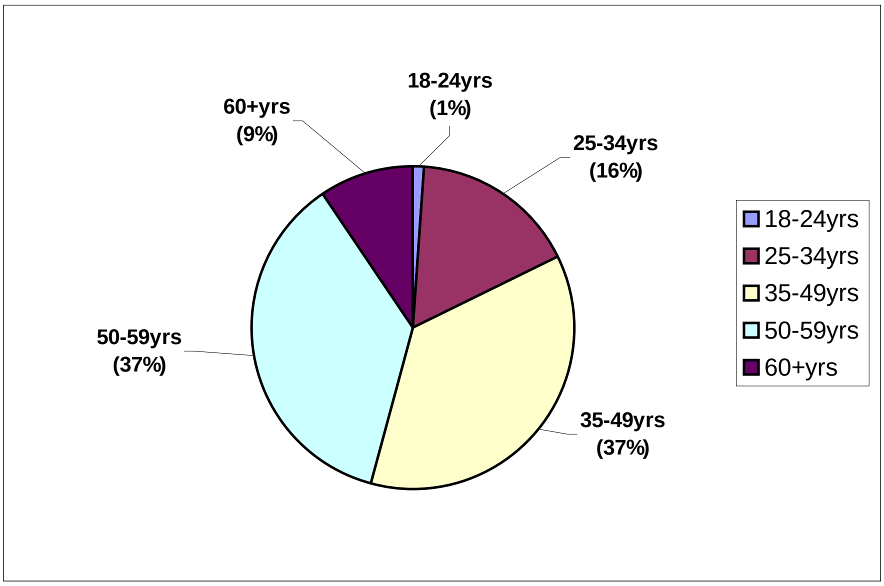

Figure 4.6: Age Distribution of Water Users

***Gender** (Responses to the Q2 of the questionnaire)*

There were 30 females and 55 males among the 85 residential WUs who participated in the survey. The percentage gender distribution is shown in Figure 4.7.

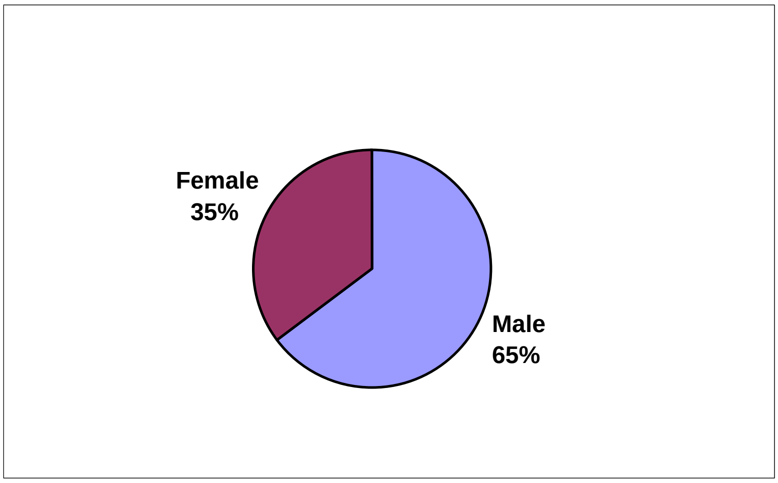

Figure 4.7: Gender Distribution of Water Users

***Retail Water Company** (Responses to the Q3 of the questionnaire)*

Currently, there are three retail water companies, viz. City West Water (CWW), South East Water (SEW) and Yarra Valley Water (YVW), servicing the Melbourne metropolitan region. The distribution of retail water companies that the survey participants belong is shown in Figure 4.8, which can also be used as an indication of the location of their residence. The high percentage of CWW consumers indicates that the majority of the participants came from the region serviced by CWW, i.e. the western suburbs of Melbourne. Note that VU is located in the Western suburbs of Melbourne.

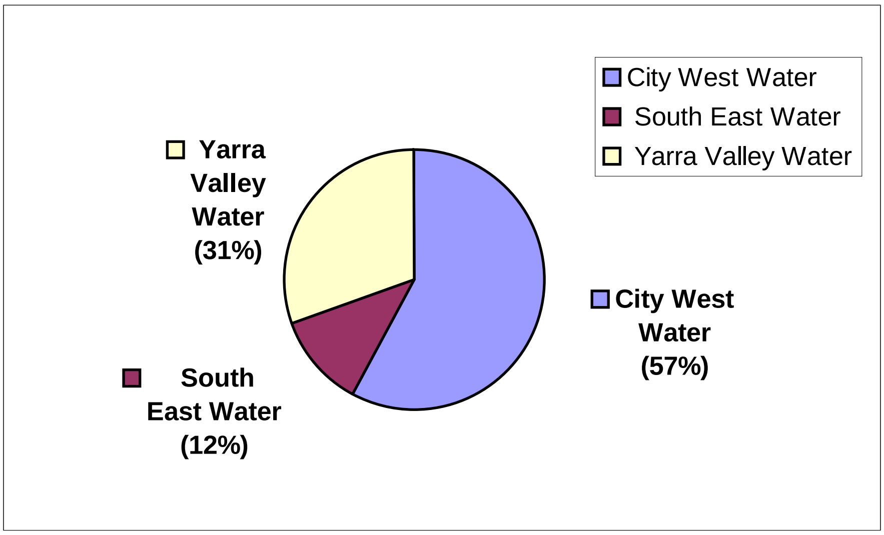

Figure 4.8: Distribution of Water Users in Retail Water Companies

***Water User Category** (Responses to the Q4 of the questionnaire)*

The responses to the Q4 made sure that all 85 participants belonged to residential water user category but not to industrial / commercial or any other category.

***Agreement with the Overall Goal** (Responses to the Q5 of the questionnaire)*

The responses to the Q5 of the questionnaire were used to understand to what extent the participants (and therefore the water users from the general public) are in agreement with the overall goal defined in Section 4.5. An overwhelming 80 WUs (94.1% of the participants) totally agreed with the goal, 4 WUs (4.7% of the participants) were in partial agreement, while only one WU (1.2% of the participants) did not agree with this overall goal. A graphical representation of the results is shown below in Figure 4.9.

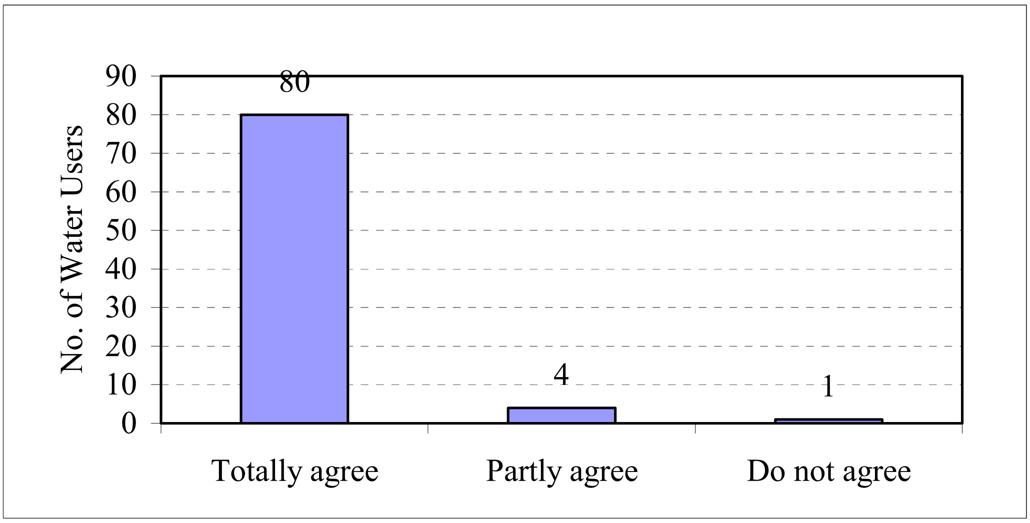

Figure 4.9: Water Users' Agreement with the Overall Goal

As highlighted in Section 4.5.1, the total or partial agreement with the stated goal was considered to be central for the optimisation of the objectives in this study. Therefore, the single response, which did not agree with the overall goal, was not included in the subsequent analysis.

(b) Preference Functions – WUs

The preference functions for WUs were derived from the responses of Q6 to Q15 in the questionnaire. Q6 was a screening question where those who 'strongly oppose restrictions' did not require answering the questions on either 'Duration of Restriction' (Q8) or 'Reliability of Supply' (Q9). They were assigned with Type I curve for both PM1 – Reliability of supply (SR) and PM3 – Duration of restrictions (DR), indicating their zero tolerance below 100% supply reliability. Those who 'Preferred no restrictions' were assigned with a Type III curve (V-shaped generalised function type where $q = 0$) for PM3 - Duration of restrictions (DR).

As can be seen from Figure 4.10, there was only one WU who strongly opposed the restrictions and eight WUs who preferred not to have water restrictions. Those who preferred no restrictions were hesitant about the issue of restrictions and they would neither strongly oppose nor willingly accept the restrictions. However, the majority (76) of the water users surveyed indicated that they would willingly accept the restrictions if it proved to be necessary as part of drought response.

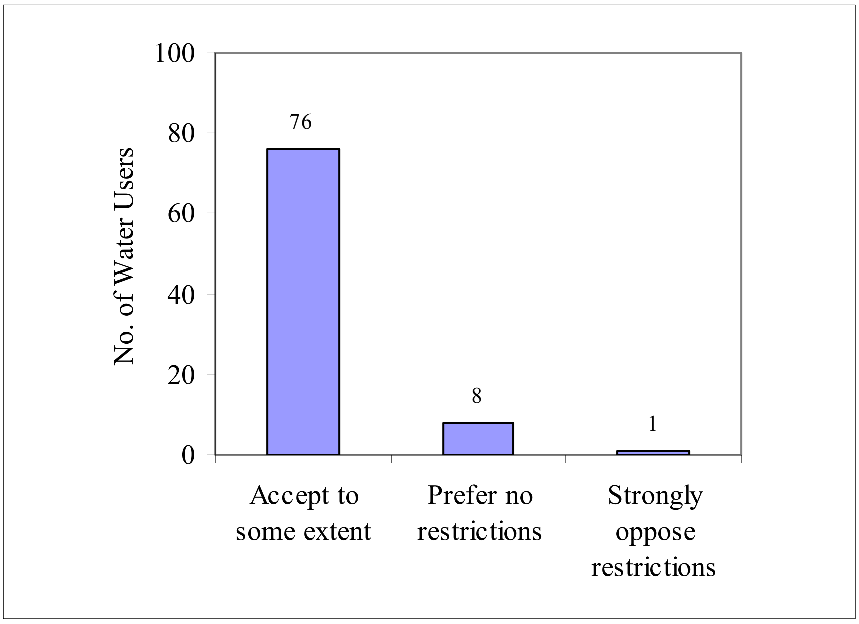

Figure 4.10: Water Users' General Perception on Water Restrictions

Q7 responses were used to derive PFs for PM3 – Duration of restrictions. In cases where the respondents indicated their willingness to accept restrictions continuously, the duration was assumed to be 10 years for calculation purposes of this study. The percentage of WUs expressing their desire for the decisions to be taken by the authorities on matters relating to pumping / treatment costs, hydropower revenue, river flows and minimum reservoir storages are given in Figure 4.11.

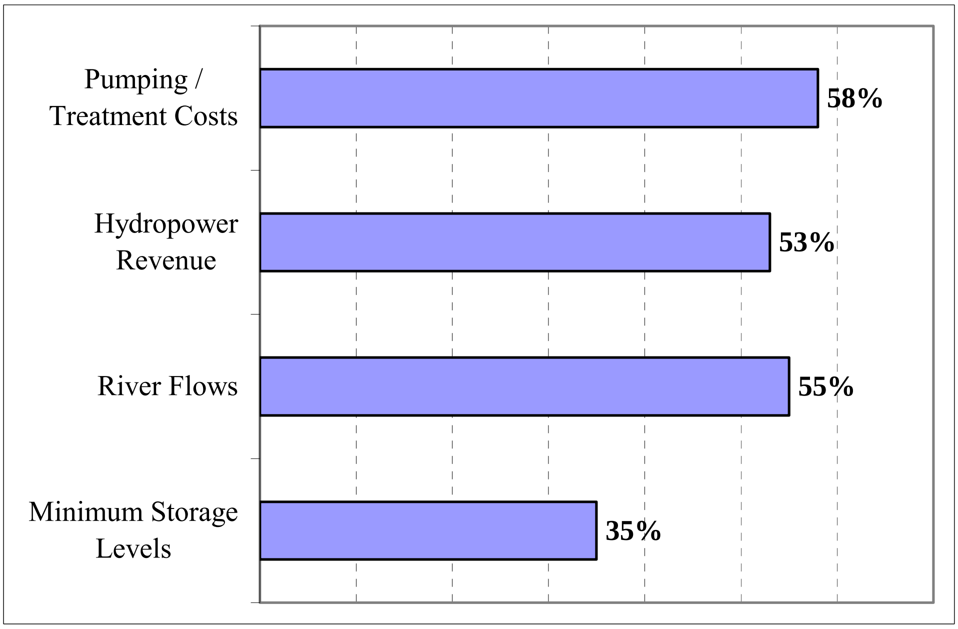

Figure 4.11: Percentage of Water Users who agreed with the RMs Preferences

It is interesting to note that only 35% of the WU participants commented that the minimum storage levels should be decided by the water authority as necessary, compared to over half of the participants expressing pumping/treatment, hydropower and river flows to be decided by the water authority ‘as necessary’.

The *p* and *q* values were calculated from the survey responses as explained in Section 4.5.1.2 (a). In special cases where WUs have ticked the ‘As necessary ‘ option, their individual preferences on that particular PM were assumed to be similar to that of the majority RMs’ preferences. The numerical values of *p & q* derived from the 84 WU survey responses (WU43 responses were excluded due to the disagreement with the overall goal) are given in Appendix G2.

Since one’s judgement on the preference threshold value ‘p’ is having an influence of his / her ‘q’ value on any PM, *p* and *q* values are considered to be dependent on each other. Therefore, the *p* and *q* values are always considered together, and are treated as ‘categorical’ (or nominal) data in the analysis (Keller and Warrack 2003). The paired *p & q* values for WUs are graphically shown (bar charts) in Figure 4.12. For each combination of *p* (*x*-axis) and *q* (*y*-axis), a frequency, *n* is indicated (*z*-axis). There is clear majority for combined p & q values on six PMs, i.e. DR, FR, PC, HR, RF and MS. However, in the case of SR and WL, the majority is not as prominent as for other PMs.

(c) Weights – WUs

WU survey responses on weight elicitation were used to calculate the final weight values of PMs for 83 WUs in a similar fashion to that explained in Section 4.5.2.1 (c) for RMs, employing the ‘Revised Simos Procedure’ (Figueira and Roy 2002).

It is noted that one WU survey respondent (i.e. WU23) did not wish to participate in the weight elicitation part of the survey, and another WU survey respondent (i.e. WU43) did not agree with the overall goal, and hence they were excluded from the analysis. Final weights on PMs calculated on WUs’ responses are given in Table 4.8. The frequency distributions for weight values of the eight PMs are given in Figure 4.13.

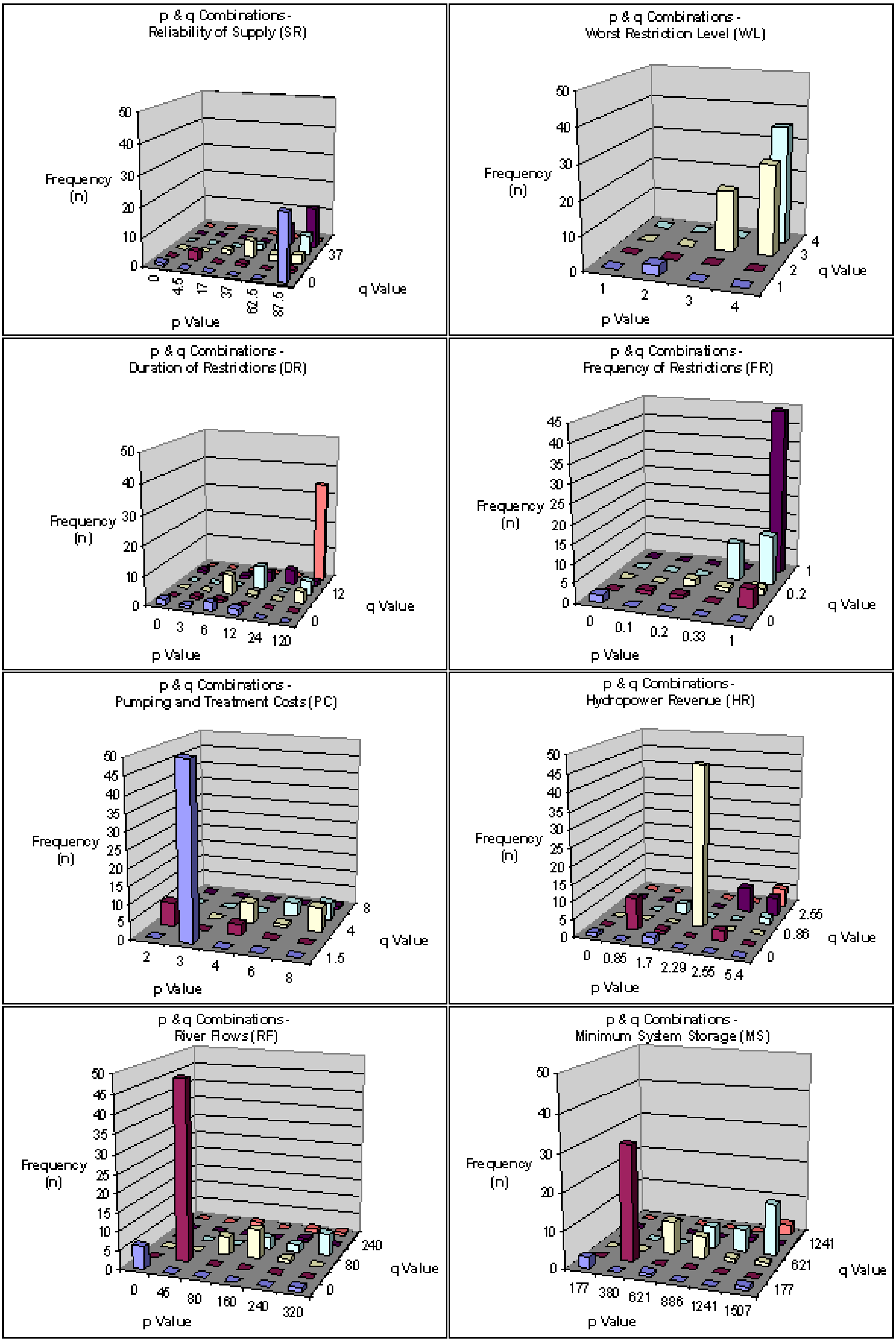

Figure 4.12: Paired *p* and *q* Values of the PMs – Water Users

Table 4.8: Water Users' Final Weights on PMs

Identification No.	SR	WL	DR	FR	PC	HR	RF	MS
WU1	1	5	3	1	3	4	28	56
WU2	2	9	7	1	5	3	32	42
WU3	6	4	7	5	3	0	32	41
WU4	2	2	2	2	5	1	31	57
WU5	2	1	1	2	5	3	56	31
WU6	6	9	11	6	2	3	14	50
WU7	6	7	6	1	5	0	30	45
WU8	3	5	4	6	4	1	32	45
WU9	8	8	2	14	4	2	54	9
WU10	0	0	0	0	11	6	33	49
WU11	6	4	5	6	8	9	28	33
WU12	6	2	5	4	2	18	30	33
WU13	6	7	6	4	10	6	33	28
WU14	3	4	5	6	3	1	36	43
WU15	5	8	7	7	5	11	9	47
WU16	6	3	3	4	3	6	28	47
WU17	2	1	1	1	6	8	32	50
WU18	6	4	3	5	4	1	32	45
WU19	3	5	3	2	3	2	33	48
WU20	5	3	4	7	4	1	32	45
WU21	4	4	4	4	5	5	51	22
WU22	5	2	4	6	6	2	32	42
WU23	Not responded							
WU24	4	7	6	3	7	3	40	30
WU25	8	5	7	9	6	7	38	21
WU26	8	5	7	9	5	0	20	45
WU27	7	4	5	7	16	4	30	27
WU28	4	14	9	10	17	6	30	12
WU29	6	7	5	3	5	10	27	37
WU30	6	8	7	7	8	9	21	34
WU31	5	7	4	6	17	6	27	30
WU32	5	5	5	5	6	5	42	29
WU33	8	7	9	1	15	10	25	25
WU34	5	3	12	15	15	12	17	21
WU35	32	40	2	6	5	6	5	4
WU36	6	5	5	6	2	2	42	32
WU37	5	2	6	3	7	2	28	47
WU38	4	3	3	4	5	2	33	47
WU39	6	9	4	3	4	14	26	35
WU40	1	3	17	4	13	18	21	23
WU41	3	8	6	5	12	5	33	28
WU42	11	8	9	10	5	2	25	31
WU43	Not agreeing with the goal							
WU44	2	4	6	5	7	3	25	48
WU45	2	8	5	7	6	2	31	40
WU46	17	0	8	36	9	4	25	1
WU47	7	15	9	1	2	2	15	50
WU48	4	9	6	2	8	6	29	36
WU49	5	4	3	4	4	3	34	43
WU50	5	4	7	6	7	10	33	28
WU51	6	4	5	8	7	2	15	56
WU52	1	3	1	2	2	4	57	31
WU53	4	8	6	2	5	5	40	30
WU54	1	2	1	2	3	3	31	57
WU55	7	2	9	3	17	13	40	10
WU56	6	1	8	7	6	4	29	40
WU57	3	7	6	4	7	3	30	40
WU58	2	3	3	2	31	9	20	30
WU59	6	9	8	5	4	2	50	17
WU60	9	10	8	3	16	4	10	40
WU61	5	5	7	6	9	7	29	32
WU62	2	3	2	2	10	7	43	30
WU63	4	3	6	5	3	5	33	42
WU64	2	6	5	3	1	6	34	43
WU65	7	5	3	6	3	4	57	14
WU66	13	2	6	19	13	7	30	10
WU67	6	6	4	5	9	8	33	28
WU68	3	6	5	2	2	3	51	28
WU69	14	3	9	12	9	4	21	29
WU70	4	3	5	7	4	1	32	45
WU71	6	5	6	5	9	8	35	26
WU72	6	2	3	5	4	1	45	35
WU73	3	1	2	2	16	15	19	42
WU74	4	3	6	7	8	0	33	39
WU75	2	1	2	2	12	7	31	43
WU76	2	3	2	1	16	7	31	38
WU77	13	3	7	9	3	2	18	45
WU78	6	4	4	5	5	5	33	40
WU79	9	6	10	7	1	4	18	45
WU80	2	2	3	2	8	7	42	35
WU81	2	15	1	8	1	0	13	61
WU82	0	1	0	1	21	1	43	33
WU83	4	4	5	4	8	9	34	34
WU84	0	0	0	0	17	0	49	33
WU85	13	9	10	12	15	7	0	33

It is noted that the frequency distributions of all four 'Level of Service' related PMs (i.e. SR, WL, DR and FR) and both the 'Costs/Revenue' related PMs (i.e. PC and HR) are positively skewed whereas the remaining two PMs (i.e. RF and MS) are closer to bell-shaped normal distributions.

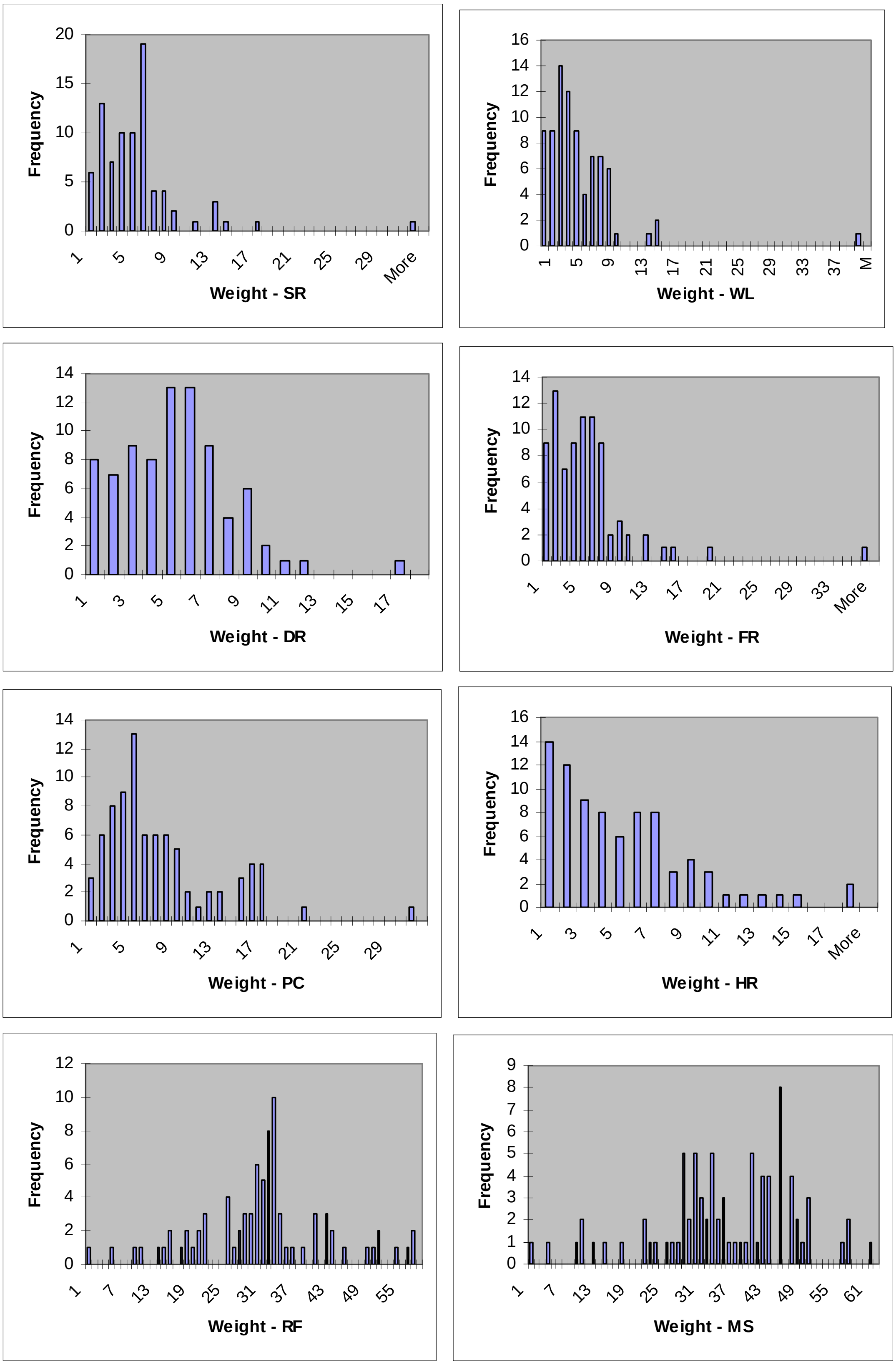

Figure 4.13: Frequency Distributions on PM Weights – Water Users

4.5.2.3 Survey Results with ENs

The process of eliciting the preferences on PMs from the ENs was similar as for the WUs. The same interview process was undertaken and the preference functions were derived from the survey responses.

(a) Agreement with the overall goal

In responding to the (Q1) of the EN questionnaire (Appendix F), all the ENs expressed a total agreement with the overall goal.

(b) Preference Functions – Environmentalist Group

The numerical values of p & q derived from the EN survey responses are given in Appendix G3. The paired q & p values for 6 ENs are also graphically presented (bar charts) in Figure 4.14.

For each combination of p (x-axis) and q (y-axis), a frequency, n is indicated (z-axis). For similar reasons stated as for WUs [Section 4.5.2.2 (c)], these combined p & q values were treated as 'categorical' in the analysis. All PMs, except 'Pumping/Treatment Costs (PC)', showed a clear majority for the combined p and q. In the special case of PC, every EN indicated a different p & q value.

(c) Weights – Environmentalist Group

The intermediate weights for PMs and objectives for ENs are calculated using the Revised Simo's Procedure described in Figueira and Roy (2002) in a similar way to RMs [Section 4.5.2.1. (c)]. The ranks assigned by the ENs for each PM and the resultant intermediate weights of PMs computed are given in Table 4.9. Table 4.10 shows the ranks assigned by the ENs for each objective and the resultant objective weights computed.

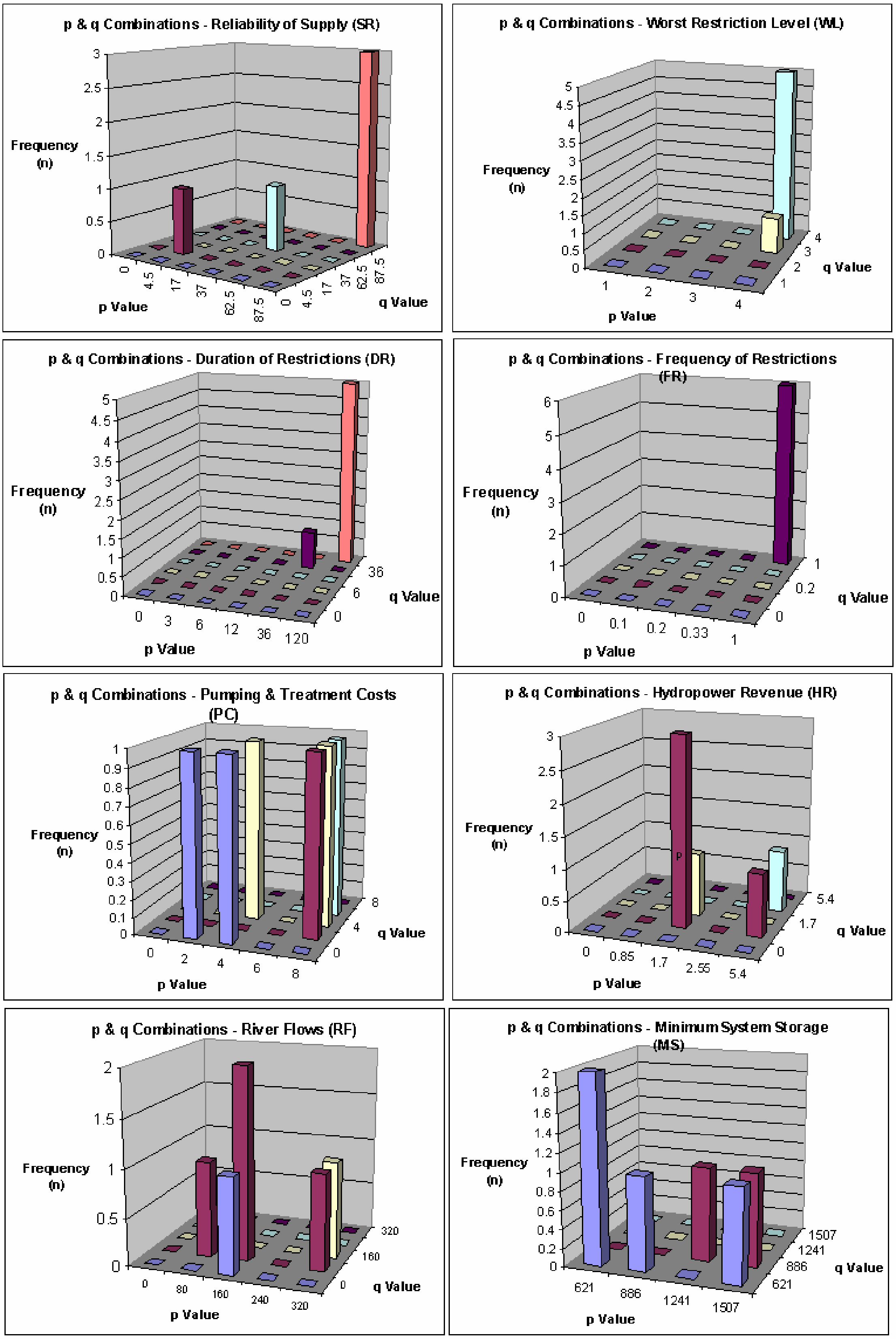

Figure 4.14: Paired *p* and *q* Values of the PMs – Environmentalists

Table 4.9: Ranks and Intermediate Weights of PMs - Environmentalists

		Performance Measures (PMs)							
		SR	**WL**	**DR**	**FR**	**PC**	**HR**	**RF**	**MS**
EN1	Rank	3,4 & 5	6	3,4 & 5	3,4 & 5	1	2	8	7
	Weight	**13**	**15**	**13**	**13**	**0**	**2**	**23**	**21**
EN2	Rank	5	4	6	3	1	2	8	7
	Weight	**13**	**11**	**15**	**10**	**2**	**4**	**24**	**20**
EN3	Rank	2	4	1	3	5	7	6	8
	Weight	**3**	**11**	**0**	**5**	**13**	**21**	**18**	**29**
EN4	Rank	2,3 & 4	1	2,3, & 4	2,3, & 4	5 & 6	5 & 6	7	8
	Weight	**5**	**0**	**5**	**5**	**18**	**18**	**23**	**26**
EN5	Rank	1,2,3,& 4	1,2,3,& 4	1,2,3,& 4	1,2,3,& 4	5	6	7 & 8	7 & 8
	Weight	**3**	**3**	**3**	**3**	**16**	**18**	**28**	**28**
EN6	Rank	5	1	4	3	2	6	8	7
	Weight	**14**	**1**	**9**	**6**	**4**	**19**	**26**	**21**

The final weights of the PMs were calculated by applying the objective weight factor to the intermediate weights of PMs. The value of this objective weight factor was based on the corresponding objective weight value calculated for each of the EN, which is given in Table 4.10.

Table 4.10: Ranks and Normalised Weights of Objectives - Environmentalists

		Objectives			
		Level of Service	**Cost / Revenue**	**Environment**	**Supply Sustainability**
EN1	Rank	2	1	4	3
	Weight	**16**	**5**	**45**	**34**
EN2	Rank	2	1	4	3
	Weight	**22**	**4**	**40**	**34**
EN3	Rank	1	2	3	4
	Weight	**5**	**16**	**32**	**48**
EN4	Rank	1	2	3 & 4	3 & 4
	Weight	**0**	**17**	**42**	**42**
EN5	Rank	2	1	3 & 4	3 & 4
	Weight	**18**	**4**	**39**	**39**
EN6	Rank	2	1	4	3
	Weight	**22**	**5**	**39**	**34**

The final (rounded) weights of PMs thus calculated for ENs are given in Table 4.11. These weight values were considered as weight parameters for the individual EN in the analysis.

Table 4.11: Final (Rounded) Weights of PMs – Environmentalists

Objective Category	Performance Measure	Environmentalist																							
		EN1				EN2				EN3				EN4				EN5				EN6			
		Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**	Weight on PM	Weight on Objective	Final Weight	**Final Rounded Weight**
LS	**SR**	13	16	3.85	**4**	13	22	5.84	**6**	3	5	0.79	**1**	5	0	0	**0**	3	18	4.5	**5**	14	22	10.3	**10**
	WL	15	16	4.44	**4**	11	22	4.94	**5**	11	5	2.89	**3**	0	0	0	**0**	3	18	4.5	**5**	1	22	0.73	**1**
	DR	13	16	3.85	**4**	15	22	6.73	**7**	0	5	0	**0**	5	0	0	**0**	3	18	4.5	**5**	9	22	6.6	**7**
	FR	13	16	3.85	**4**	10	22	4.49	**4**	5	5	1.32	**1**	5	0	0	**0**	3	18	4.5	**5**	6	22	4.4	**4**
Sub Total		54		16		49		22		19		5		15		0		12		18		30		22	
CR	**PC**	0	5	0	**0**	2	4	1.33	**1**	13	16	6.12	**6**	18	17	8.5	**9**	16	4	1.88	**2**	4	5	0.87	**1**
	HR	2	5	5	**5**	4	4	2.67	**3**	21	16	9.88	**10**	18	17	8.5	**9**	18	4	2.12	**2**	19	5	4.13	**4**
Sub Total		2		5		6		4		34		16		36		17		34		4		23		5	
E	**RF**	23	45	45	**45**	24	40	40	**40**	18	32	32	**32**	23	42	42	**42**	28	39	39	**39**	26	39	39	**39**
Sub Total		23		45		24		40		18		32		23		42		28		39		26		39	
SS	**MS**	21	34	34	**34**	20	34	34	**34**	29	48	48	**48**	26	42	42	**42**	28	39	39	**39**	21	34	34	**34**
Sub Total		21		34		20		34		29		48		26		42		28		39		21		34	
			SUM	100	100			100	100			101	101			101	102			100	102				

4.5.3 Modelling of Stakeholder Preference Parameters for Group Decision Analysis

To illustrate the idea of group decision-making in this study, it was decided to form two hypothetical Decision-making Groups (DMGs) comprising individual RMs and representations from WUs and ENs. For this purpose, the input preference parameters (PFs and weights on PMs) were needed for:

- Individual RM's,
- Representative WU (WU_{rep}), and
- Representative EN (EN_{rep}).

The details of individual RMs' PF and weights on PMs as derived earlier are given in Tables 4.3 and 4.7 respectively. However, in modelling WU_{rep}'s and EN_{rep}'s preference parameters, it was necessary to derive single sets of representative PFs (with its q and p values) and weights for eight PMs.

As described in Sections 4.5.2.2 (b) and 4.5.2.3 (b), the paired *p* and *q* values were considered as 'categorical'; the values of these variables are categories and do not have a numerical meaning to its category label (Keller and Warrack 2003). Therefore, a representative *p* and *q* for each PM was taken as the modal value, representing the most number of occurrences in a category. However, in the special case of every participant giving a different *q* and *p* combination for a PM (eg. PM5 for ENs), a random combination for *q* and *p* was chosen as the representative value for the group. The values of *q* and *p* automatically fixed the PF type (assuming Type V curve and its variants). Details of PFs thus derived for WU_{rep} and EN_{rep} are presented in Table 4.12.

Table 4.12: Representative Water User and Environmentalist Preference Functions

	SR	**WL**	**DR**	**FR**	**PC**	**HR**	**RF**	**MS**
$\mathbf{WU_{rep}}$	Type III $q = 0$ $p = 87.5$	Type II $q = 4$ $p = 4$	Type II $q = 120$ $p = 120$	Type II $q = 1$ $p = 1$	Type V $q = 1.5$ $p = 3$	Type V $q = 0.86$ $p = 2.29$	Type V $q = 18.3$ $p = 45$	Type V $q = 208$ $p = 380$
$\mathbf{EN_{rep}}$	Type II $q = 87.5$ $p = 87.5$	Type II $q = 4$ $p = 4$	Type II $q = 120$ $p = 120$	Type II $q = 1$ $p = 1$	Type II $p = 2$ $q = 2$	Type V $q = 0.85$ $p = 1.7$	Type V $q = 80$ $p = 160$	Type II $q = 621$ $p = 621$

To arrive at single representative PM weight values for WUs and ENs in a group decision-making situation, the median was considered as the representative value, since it agrees with the majority view of the group (Hokkanen and Salminen 1994). One other advantage of the median value is that it is not as sensitive to extreme values as the mean value (Keller and Warrack 2003). The final weights on PMs thus derived for WU_{rep} and EN_{rep} together with the final weights for 6 RMs (Table 4.7) are summarised in Table 4.13.

Table 4.13: Normalised Weights of PMs - Individual Decision Makers

	Performance Measure (PM)							
	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
RM1	9	18	13	10	17	0	0	33
RM2	7	8	8	7	12	11	27	20
RM3	4	8	3	5	1	0	20	58
RM4	1	3	1	4	10	8	27	45
RM5	11	14	12	9	25	11	0	18
RM6	8	4	7	5	1	0	38	38
WU_{rep}	5	4	5	5	6	4	33	37
EN_{rep}	5	4	5	4	1	5	40	37

In the decision analysis discussed in Chapter 5, it was possible to consider the individual RMs or the representatives of the WUs or ENs as the DMs. The above preference parameters (PFs and weights on PMs) of the three stakeholder groups were used in several single DM situations and group decision-making situations, as input parameters to *Decision Lab 2000* software in the analysis.

4.6 Summary

MCDA software tools built into Decision Support Systems may provide further support for the water resources managers to systematically incorporate the stakeholder preferences in the decision making process. Recent literature suggest that, there is a growing shift towards the methodical inclusion of stakeholder preferences in practical decision making situations related to sustainable water resources management.

The stakeholder preferences often have a great influence on the final decision, at the same time, bringing in some uncertainty into the decisions. Therefore, preference elicitation and modelling is an area, which should be handled carefully, to reflect the stakeholders' views as accurately as possible. Further, the stakeholder preference parameter evaluations are considered to be subjective in nature and tend to vary for reasons stretching beyond the characteristics of the decision problem. Also, in the context of decision aiding, determining the stakeholder preference parameters is considered to be a difficult and tedious process.

This chapter described the detailed methodology used to elicit stakeholder preference parameters for the case study, as required by PROMETHEE and *Decision Lab 2000*. The preference elicitation process comprised of an interviewer-assisted questionnaire survey to derive the preference functions and weights for the performance measures (PMs) from stakeholders of the Melbourne water supply system. Representatives from three major stakeholder groups (i.e. RMs, WUs and ENs) participated in an interviewer assisted questionnaire survey to express their preferences on the eight PMs identified in Chapter 3.

A total of 97 participants were recruited for the survey from Melbourne Water (MW) and Victoria University (VU) representing the categorisation of stakeholder groups. This chapter also explained the formulation of the survey methodology, the structure of the questionnaire, the results of the questionnaire interview survey and the modelling of stakeholder preference parameters. The representative preference threshold values and the corresponding weight values for the three stakeholder groups were also derived as input parameters to Decision Lab 2000 software. These preference parameters will be used in a group decision-making situation, to choose optimum operating rules for Melbourne Water supply system.

Though eliciting preference intensities from the resource managers was seemed to be straightforward using the generalized preference function types proposed in the PROMETHEE method, the need for developing an indirect approach was identified for other stakeholder groups who are not familiar with either the feasible ranges of PM values or the generalized preference function types described in PROMETHEE method.

The ‘Revised Simos’ Procedure’, the technique used to collect information on weights, proved to be well accepted by the respondents. The approach of modelling preference parameters described in this chapter enables the evaluation and comparison of the alternative operating rules when PM values are available for each operating rule. The evaluation of alternative operating rules in the case study example, using the preference parameters derived in this chapter are discussed in Chapter 5.

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Chapter 5: Sensitivity Analysis, Robustness Measures and Derivation of Optimum Operating Rules

5.1 Introduction

The uncertainty appears throughout the decision analysis process from its early stages of choosing the Multi-Criteria Decision Aiding (MCDA) method, to the final stages of explaining and recommending the results, e.g. optimum operating rules for Melbourne water supply system in the case study example. The implications of these uncertainties need to be examined in order to render the Decision Makers (DMs) with the necessary confidence to make justifiable decisions with reasonable certainty. Parameter uncertainty is one of the most discussed areas in MCDA, where sensitivity and robustness studies are employed to understand the effects of the parameter variations on the results.

As discussed in Figure 2.2, sensitivity analysis and robustness evaluations are regarded as key stages in discrete MCDA where the DM is able to explain the results and make the recommendations with confidence. Through these analyses, the DMs are able to judge how much of uncertainty in the output of a model is influenced by the uncertainty in its input parameters. In MCDA applications, the sensitivity analysis and robustness measures have been used in the past in many different circumstances for many different purposes.

In Chapter 4, the characteristics of preference parameters required for MCDA was discussed, and the stakeholder preference parameters were modelled for the case study. These preferences, which were modelled for each stakeholder group [i.e. Resource Managers (RMs), Water Users (WUs), and environmental interest groups (ENs)] together with the Performance Measures (PMs) evaluations given in the form of a decision matrix (Table 3.10) was used to derive the optimum operating rules for Melbourne water supply system.

Pomerol and Barba-Romero (2000) state that the sensitivity analysis with ‘what-if’ notions in discrete MCDA could be divided into two main levels: those concerning the input data (first level) and those concerning the MCDA models (second level). However, the case study in this thesis will cover only the first level of sensitivity analysis concerning the possible inconsistencies in some input data. The *Decision Lab 2000*'s in-built sensitivity analysis and robustness measures deal with only two types of input parameters, they are:

- Stakeholders' PM weights, and
- Weights given to individual actors in a decision making group (DMG)

The case study results, i.e. final PROMETHEE II ranking of alternative operating rules, were examined for their sensitivity and robustness related to different acceptable values of PM weights given by the individual DMs and group compositions.

The current chapter illustrates the derivation of optimum operating rules for Melbourne water supply system under different group decision-making scenarios, with special focus on the importance in sensitivity and robustness measures to examine the effect of the parameter uncertainty on the MCDA outcome. A discussion on the sensitivity and robustness measures related to MCDA that have been reported in the MCDA literature is included in Section 5.2. Particular reference is made to the literature that address the effect of the variations in preference parameters on the conclusions drawn from MCDA analyses related to water resources planning and management applications. Then, the typical features in *Decision Lab 2000* software are detailed in Section 5.3, highlighting its capabilities to handle sensitivity analysis of the results and to deal with Group Decision Making (GDM) situation through multi-scenario analysis.

Then, the derivation of optimum operating rules for the case study is described in Section 5.4, followed by a discussion on sensitivity and robustness of the results. The decision analysis process involved the ranking of alternative operating rules, and studying the sensitivity and robustness of the rankings obtained, utilising the capabilities of *Decision Lab 2000* software. Section 5.4.1 details the initial investigation of the problem under several single DM and GDM scenarios considered for the case study. Section 5.4.2 illustrates the decision analysis process under two GDM situations. The derivation of optimum operating rules is presented in Section 5.4.3. The sensitivity of the optimum operating rule on the weights assigned to the individual actors in two

GDM situations are examined in Section 5.4.4. Finally, the robustness of the results under varying group compositions is discussed in Section 5.4.5.

5.2 Sensitivity Analysis and Robustness Measures in Discrete MCDA

The output results of discrete MCDA critically depend on the quality of data input. Rios Insua (1990) classified the data inputs into two types, while claiming that the excellence of an application of a decision aid will depend not only on the goodness of the calculation procedure, its theoretical foundations and numerical precision, but also on the quality of the data input. The two types of data inputs are:

- 'Objective data' - they refer to the performance characteristics (or PM evaluations) of the alternatives
- 'Subjective data' - they refer to the DM's judgemental inputs (or preference thresholds and weights on PMs)

Mareschal (1986) pointed out that the uncertainty of data in MCDA appears for two main reasons: Firstly, there is a technical reason due to the evaluation procedures, where the measurement instruments and the human judgements are often leading to uncertainty. Secondly, the more structured reason for uncertainty, as he points out, is that many PMs are difficult to be quantified and cannot easily be represented by a single value. The uncertainty analysis that is dealt with in the case study will be demonstrated on the first type of data related to human judgements.

To address the second kind of uncertainty, i.e. of PM evaluations, Mareschal (1986) proposed a stochastic extension to the PROMETHEE outranking method. Since PROMETHEE flows are linear combinations of the preference functions, the distribution of the differences of PM evaluations was used to compute an 'Expected Preference Function', which was introduced to handle the stochastic nature of a problem. A similar stochastic approach to PROMETHEE is proposed by D'Avignon and Vincke (1988), which transforms the distributive evaluations of alternatives according to DM's preferences.

It is common in MCDA to examine the sensitivity of output for possible variations in PM weights or PM evaluations. Delgado and Sendra (2004) claim that the sensitivity analysis in MCDA models are mostly based on the variation of the weights of the PMs implied in the process to test whether it significantly modifies the results obtained. However, any attempts to study the sensitivity due to preference threshold values, such as in PROMETHEE type outranking methods, were rarely sighted in literature.

Hyde et al. (2003) addressed the issue of uncertainty of input data concerning PM weights and PM evaluations by a stochastic approach. This approach involved defining the uncertainty in the input data using probability distributions, performing a reliability analysis by Monte Carlo simulation and undertaking a significance analysis using the Spearman rank correlation coefficient. Reliability analysis provides the DMs with the distributions of the total values (derived by weighted sum method described in Section 2.3) for single alternative or the difference between values for competing alternatives. Significance analysis identifies the most important input parameters, which helps DMs with concentrating on characterising their uncertainty. The approach utilised all the available data, including the expected ranges of PM evaluations and the PM weights given by multiple actors in a group.

They also claim that although many researchers (e.g. Barron and Schmidt 1988; Mareschal 1988; Triantaphyllou and Sanchez 1997) have proposed various MCDA technique-specific sensitivity analysis methods, each of these methods is limited in its ability to resolve the inherent uncertainties in the MCDA process. Their (proposed) stochastic approach was demonstrated on two water resource allocation case studies investigated by Srinivasa Raju et al. (2000) and Fleming (1999). They concluded that this approach enables a DM to examine the robustness of a solution and giving the confidence to a DM to make a decision with reasonable certainty.

Many other authors (e.g. Pomerol and Barba-Romero 2000; Rios Insua 1990; Vincke 1999) have also highlighted that it is essential to critically review the input data in MCDA and examine the sensitivity of the results to the different plausible sets of these data, since in MCDA process, the data input is constantly revised as the DM wishes to understand the implications and possible inconsistencies of his/her judgements. It can also be seen from Table A-2 (Appendix A) that in a vast majority of cases, many MCDA software developers incorporate sensitivity analysis of data to a certain extent, within the software programs.

Pomerol and Barba-Romero (2000) describe three types of questions that a software program could answer in order to deal with sensitivity analysis concerning the subjective input data:

Q1 - Does the order (or ranking) change if the parameters (weights/preference thresholds etc.) are changed by a given amount?
Q2 - By how much can the given parameters vary without affecting the final ranking?
Q3 - Can ranges be given to parameters that leave the final result unchanged?

They also state that most software applications reply to Q1 by supplying the new results, whereas the validity limits of PM weights (Q2) are given by *Decision Lab 2000* (Visual Decision 2003) and DEFINITE (Herwijnen and Janssen 1989). Q3 is dealt with by TRIMAP (Climaco and Antunes 1989) and *Decision Lab 2000* with respect to PM weights.

Rios Insua (1990) points out that the sensitivity analysis can focus on those judgemental inputs which are most important in determining the final choice and therefore, need to be revised most carefully. He also suggests that after a sensitivity analysis with respect to uncertain input data, the DM should have a better picture of the decision problem so he/she might be able to make some holistic comparisons.

The uncertainties in water supply system operations may appear due to varying streamflow conditions, varying demand conditions or varying DM preferences on system PMs. Although there could be considerable amount of uncertainty due to varying streamflow and demand conditions (related to the PM evaluations), this aspect was beyond the scope of the case study application described in Section 5.4, but the main focus is given only to the possible variations of DM preferences. The varying DM preferences usually arise where a single decision is to be agreed upon by a group of DMs. Therefore, the case study example in this report, dealt with a single decision matrix (Table 3.10) and varying DM preference parameters (discussed in Chapter 4).

The case study results are derived and analysed for two DMGs defined in Section 5.4.1. The *Decision Lab 2000* software provides a comprehensive sensitivity analysis for PM weights in a single DM case. However, for GDM setting, it does not facilitate the sensitivity analysis of PM weights given by the individual actors, instead the sensitivity analysis is facilitated through the weights assigned to individual actors in the group. Therefore, the sensitivity analysis carried out for the case study covered the uncertainty involved with the group composition of the DMG (i.e. weights given to different actors in the DMG).

5.3 *Decision Lab 2000* Software

As discussed in Section 2.7, one of the most known and widely used outranking methods, PROMETHEE with its current software implementation, *Decision Lab 2000* was chosen for this study. *Decision Lab 2000* is a Windows application that uses a typical spreadsheet interface to manage the data and GAIA (**G**eometrical **A**nalysis for **I**nteractive **A**ssistance) visual interactive module to understand the structure of an MCDA problem.

The software has been developed by the Canadian company Visual Decisions Inc., in collaboration with the authors of PROMETHEE method, Professor Jean-Pierre Brans and Professor Bertrand Mareschal at Brussels Free University, Belgium (Brans and Mareschal 2005). It is an improved version of the PROMCALC decision support software (Brans and Mareschal 1994) which has been previously used in many applications (e.g. Cil et al. 2005; Genova et al. 2004; Martin et al. 1999; Mladineo and Knezic 2003; Rogers et al. 2004).

As explained in Section 2.7.2, the PROMETHEE algorithm is based on the principle of pair-wise comparison of alternatives. The GAIA is a descriptive compliment to the PROMETHEE rankings, which offers a global insight of conflicts/agreements among PMs and the characteristics of the alternatives (Geldermann and Zhang 2001). GAIA makes use of the Principle Components Analysis method which is popular in multivariate data analysis (Visual Decision 2003) to give a visual understanding of the problem in hand. All the input data related to the PROMETHEE method (i.e. PM evaluations, preference functions, weights etc.) can be easily defined and fed into a single (main) window.

Decision Lab 2000 also provides the user with additional features such as the definition of qualitative PMs, the treatment of missing values in the decision matrix or the definition of percentage (variable) thresholds in the preference functions. Categories of alternatives or PMs can also be defined to better identify subgroups of related items and to analyse the decision problem. Several interactive tools and displays are available for facilitating weight sensitivity and robustness analyses. The group decision-making extension is by PROMETHEE Group Decision Support System (GDSS) procedure which is integrated in *Decision Lab 2000*, through definition of several scenarios for the same problem (Brans and Mareschal 2005).

As previously stated in Table A-2 (Appendix A), *Decision Lab 2000* is commercially available from Visual Decision Inc., Canada and comes with a comprehensive help file and a 'Getting Started Guide'. All the information about the software and methodology, a guided 'Quick Tour' and a free download of a demonstration version is available from the website www.visualdecision.com or www.smg.ulb.ac.be. For single DM case, three basic input data for the software is given below:

1. Decision matrix (as derived for the case study in Section 3.5.6). This matrix includes *n* number of PMs and their min/max character, *m* number of alternatives and (*m* x *n*) number of PM evaluations.
2. Weights of PMs (as derived for the case study in Section 4.5.3).
3. Preference functions of PMs (as derived for the case study in Section 4.5.3).

In addition to the above information from each of the DMs, for GDM, the software also requires the weights assigned for the voice of each DM (default setting is the equal weights).

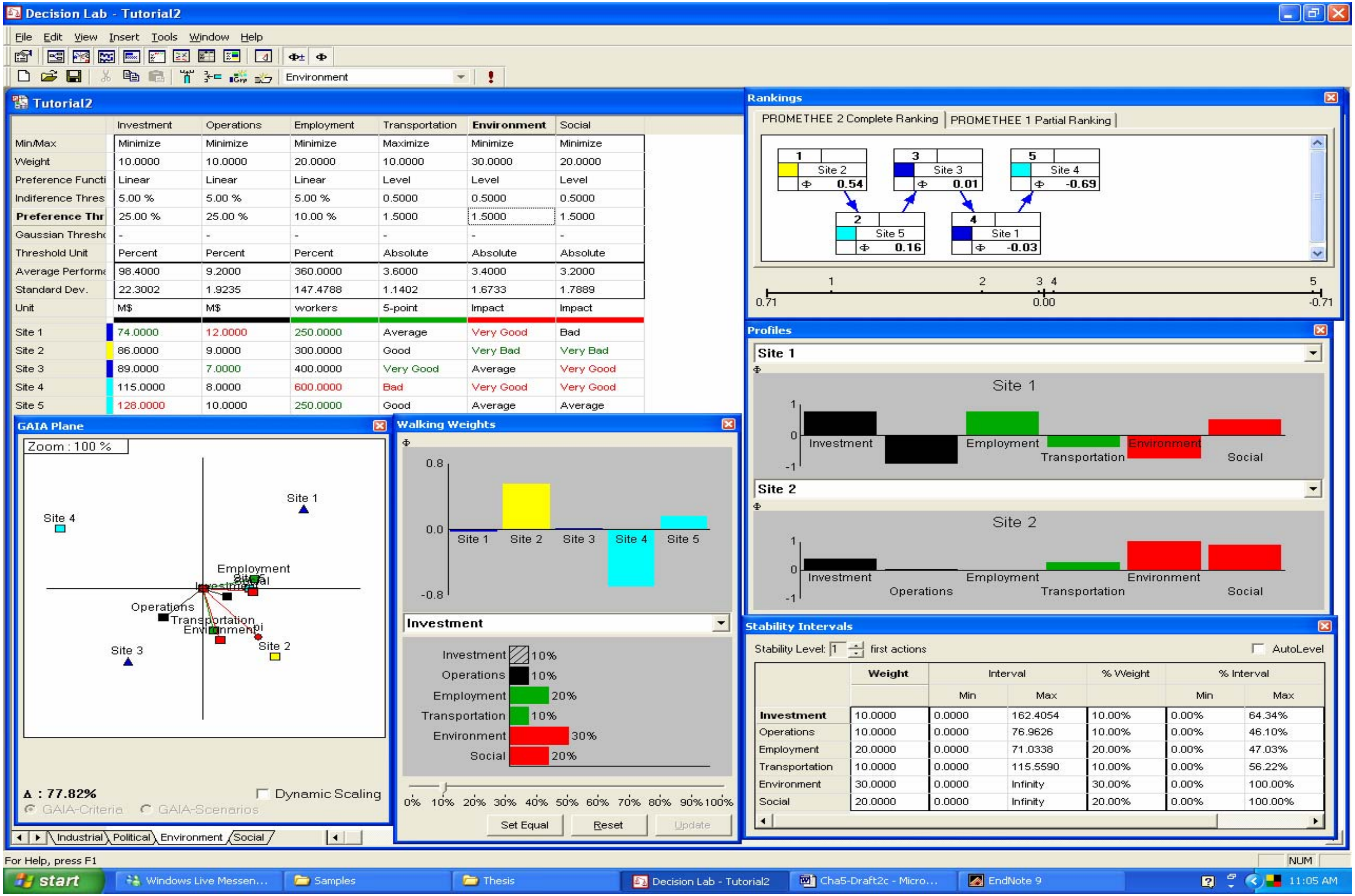
The software displays the output results in three different ways, each complementing the others (Visual Decision 2003):

- PROMETHEE I and PROMETHEE II rankings,
- Profiles of alternatives, and
- GAIA-criteria plane (for single DM case) or GAIA-scenario plane (for group decision making).

Typical input and output features of the software are illustrated in Figure 5.1 on a single display window, for a tutorial example provided within the software. A brief description of the decision problem dealt within the tutorial example is given below in order to explain the features of the software (Visual Decision 2003):

> *A company wishes to build a new plant in a given geographical region. Five potential locations have been identified for this purpose and the managers are discussing the advantages and weaknesses of each one. In such a situation, several aspects should clearly be taken into account: various costs will certainly be of interest to the company (investment cost, operating cost, employment); technical aspects such as the availability of a good local transportation network are also important; environmental and social impacts are not negligible.*

Managers have identified six relevant PMs, i.e. investment costs, operation costs, employment, transportation, environmental impact and social impact. The main input window is shown in the spreadsheet format in the top left-hand corner of the display. The input information related to the PMs (i.e. Minimise/Maximise property, weights, preference thresholds, threshold unit and the evaluations on the alternative sites) could be typed into this main window. In addition, there are five other windows shown embedded in the main window in Figure 5.1, namely, PROMETHEE rankings, profiles (of alternatives), GAIA-Plane, walking weights and stability intervals. The details of these software features are explained later in this chapter with reference to the tutorial example. .



	Investment	Operations	Employment	Transportation	Environment	Social
Min/Max	Minimize	Minimize	Minimize	Maximize	Minimize	Minimize
Weight	10.0000	10.0000	20.0000	10.0000	30.0000	20.0000
Preference Functi	Linear	Linear	Linear	Level	Level	Level
Indiference Thres	5.00 %	5.00 %	5.00 %	0.5000	0.5000	0.5000
Preference Thr	25.00 %	25.00 %	10.00 %	1.5000	1.5000	1.5000
Gaussian Threshc	-	-	-	-	-	-
Threshold Unit	Percent	Percent	Percent	Absolute	Absolute	Absolute
Average Performa	98.4000	9.2000	360.0000	3.6000	3.4000	3.2000
Standard Dev.	22.3002	1.9235	147.4788	1.1402	1.6733	1.7889
Unit	M$	M$	workers	5-point	Impact	Impact
Site 1	74.0000	12.0000	250.0000	Average	Very Good	Bad
Site 2	86.0000	9.0000	300.0000	Good	Very Bad	Very Bad
Site 3	89.0000	7.0000	400.0000	Very Good	Average	Very Good
Site 4	115.0000	8.0000	600.0000	Bad	Very Good	Very Good
Site 5	128.0000	10.0000	250.0000	Good	Average	Average

Stability Level: 1 first actions ☐ AutoLevel

	Weight	Interval		% Weight	% Interval	
		Min	Max		Min	Max
Investment	10.0000	0.0000	162.4054	10.00%	0.00%	64.34%
Operations	10.0000	0.0000	76.9626	10.00%	0.00%	46.10%
Employment	20.0000	0.0000	71.0338	20.00%	0.00%	47.03%
Transportation	10.0000	0.0000	115.5590	10.00%	0.00%	56.22%
Environment	30.0000	0.0000	Infinity	30.00%	0.00%	100.00%
Social	20.0000	0.0000	Infinity	20.00%	0.00%	100.00%

Figure 5.1: Main Input Window, Rankings, Action Profiles, GAIA-Plane, Walking Weights and Stability Intervals of the *Decision Lab 2000*

5.3.1 PROMETHEE I and PROMETHEE II rankings

PROMETHEE I shows the partial ranking of alternatives based on strongly established preferences only. Incomparable alternatives, which usually have quite different profiles or PM evaluations (see Section 5.3.2), are highlighted in PROMETHEE I ranking.

PROMETHEE II is a complete ranking, based on a numerical rating of the alternatives from the best alternative to the worst alternative, leaving no incomparable pairs of alternatives. This information is more straightforward and is easier to use than PROMETHEE I partial ranking, but it is a reflection of less reliable preferences accommodating compensation to a greater extent (Visual Decision 2003). Both these windows provide a scale at the bottom, indicating the actual distance between the alternatives, which is decided by the net preference flow (Φ) of an alternative (as explained in Section 2.7.1).

The PROMETHEE II ranking output window for tutorial example is given in the top right-hand corner of the display window shown in Figure 5.1. Considering all the input information, it identifies Site 2 (with $\Phi = 0.54$) as the most suitable location for the plant. The scale at the bottom of the window suggests that in terms of performance, the next preferred location, Site 5, is not closely matching with Site 2 (with $\Phi = 0.16$). Therefore, the managers could quite confidently recommend the choice of Site 2.

5.3.2 Profiles of Alternatives

The ‘Profiles’ (of alternatives) in *Decision Lab 2000* are used to appreciate the ‘quality’ of an alternative on the different PMs and it is extensively used by DMs to finalise their appreciation (Brans and Mareschal 2005). A typical ‘Profiles’ output window is shown in Figure 5.1, which can display two alternative profiles at one time.

According to the definitions of positive and negative outranking flows given in Section 2.7.2, the net flow of an alternative ‘*a*’:

$$\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a) = 1/(\mathrm{m} - 1)\sum_{i=1}^{m} [\pi\ (a,i) - \pi\ (i,a)]$$

$$= 1/(\mathrm{m} - 1)\sum_{j=1}^{n} \{p_j[f_j(a) - f_j(i)] - p_j[f_j(i) - f_j(a)]\}w_j$$

i.e. $\Phi(a) = \sum_{j=1}^{n} \Phi_{\mathrm{j}}(a)w_j$ where

$$\Phi_{\mathrm{j}}(a) = 1/(\mathrm{m} - 1) \sum_{j=1}^{n} \{p_j[f_j(a) - f_j(i)] - p_j[f_j(i) - f_j(a)]\}$$

The symbols used in above equations are defined earlier in Section 2.7.

Brans and Mareschal (2005) defined $\Phi_{\mathrm{j}}(a)$ as the 'single criterion net flow' of alternative '*a*' and it is obtained when only one PM [i.e. $f_j(.)$] is considered (100% of the total weight is given to that PM). It expresses how an alternative '*a*' is outranking $[\Phi_{\mathrm{j}}(a) > 0]$ or outranked by $[\Phi_{\mathrm{j}}(a) < 0]$ all the other alternatives on PM $f_j(.)$. The profile of an alternative consists of the set of all single criterion net flows, $\Phi_{\mathrm{j}}(a)$, j=1,2,.., n.

Figure 5.1 shows the two action profiles for Site 1 and Site 2. In comparison, although Site 1 shows better performance on investment costs and employment, Site 2 is performing better on all other PMs, i.e. operation cost, transportation, environmental impact and social impact. With this 'Action Profiles' widow, it is possible to compare any two alternatives at one time with respect to their performance.

5.3.3 GAIA-Criteria Plane

The GAIA-criteria plane of *Decision Lab 2000* uses the matrix, M (*m* x *n*) of the single criterion net flows (as explained in Section 5.3.2) of all the sites to give a visual understanding of the decision problem alternatives (Brans and Mareschal 2005). The single criterion net flow matrix is shown in Table 5.1. It is observed that, this single criterion net flow matrix contains the preference information prescribed by generalised function types, in addition to the information contained in the decision matrix given in Table 2.1. Furthermore, the $\Phi_{\mathrm{j}}(a_i)$ values are dimensionless while $f_j(a_i)$ values are expressed on their own scale and the matrix of $\Phi_{\mathrm{j}}(a_i)$ is not dependant on the PM weights.

Table 5.1: Single Criterion Net Flows

PM Alternative	$\Phi_1(.)$	$\Phi_2(.)$	.....	.....	$\Phi_j(.)$	.....	.....	$\Phi_n(.)$
a_1	$\Phi_1(a_1)$	$\Phi_2(a_1)$	.....	.....	$\Phi_j(a_1)$	.....	.....	$\Phi_n(a_1)$
a_2	$\Phi_1(a_2)$	$\Phi_2(a_2)$	.....	.....	$\Phi_j(a_2)$	.....	.....	$\Phi_n(a_2)$
..	.....	.....	.....	.....	.....	.....	.....	.....
..	.....	.....	.....	.....	.....	.....	.....	.....
a_i	$\Phi_1(a_i)$	$\Phi_2(a_i)$	.....	.....	$\Phi_j(a_i)$	.....	.....	$\Phi_n(a_i)$
..	.....	.....	.....	.....	.....	.....	.....	.....
..	.....	.....	.....	.....	.....	.....	.....	.....
a_m	$\Phi_1(a_m)$	$\Phi_2(a_m)$	.....	.....	$\Phi_j(a_m)$	.....	.....	$\Phi_n(a_m)$

[Source: (Brans and Mareschal 2005)]

Consequently, a cloud of m points in an n-dimensional space can represent the set of the m alternatives. It is noted that this cloud is also centred at the origin. With more than two PMs, it is difficult to visualize the relative position of alternatives (m points) with respect to the PMs. The information in the n-dimensional space is therefore projected on a two-dimensional plane, in such a way that as much information as possible is preserved after projection. This two-dimensional plane is called the GAIA-Criteria plane in *Decision Lab 2000* software.

According to the 'Principal Components Analysis' technique, the GAIA plane is defined by the two eigenvectors corresponding to the two largest eigenvalues of the covariance matrix M^1M of the single criterion net flows. The GAIA-criteria plane for tutorial example is shown in Figure 5.1. In the GAIA plane, a point represents each alternative and each PM is represented by an axis. The Δ value appearing in the lower left end of the window measures the amount of information preserved after projection, and it gives an indication of the quality of the information provided by the GAIA plane. If this value is more than 75%, the information is considered to be highly reliable (Brans and Mareschal 1990) meaning that at least 75% of the information is retained during the projection. Figure 5.1 gives a Δ value of 77.82%, implying that the GAIA-criteria plane could be used to interpret the results.

The impact of the PM weights on a decision is decided by the weight vector, w: (w_1, w_2,….w_j, …w_n). The projection of the weight vector on the GAIA plane is the 'PROMETHEE decision axis', which is indicated as '*pi'* (Figure 5.1) in *Decision Lab 2000* software. If all the weights are concentrated on one PM, the PROMETHEE decision axis will coincide with the axis of this PM in the GAIA plane.

According to Brans and Mareschal (1990; 2005), if the Δ value is sufficiently high, the following properties hold:

P1: The longer the PM axis, the more it differentiates the alternatives. This also means a comparatively higher variation of the PM scores in the decision matrix.

P2: The axes oriented in approximately the same direction represent the PMs agreeing (positively correlated) with each other.

P3: The axes oriented in opposite directions represent the PMs that are conflicting (negatively correlated) with each other.

P4: The orthogonal axes represent PMs that are independent of each other.

P5: Clusters of the alternatives indicate the similar alternatives in terms of the PM evaluations.

P6: The alternatives performing well on a particular PM are represented by points located in the corresponding PM axis. The farther an alternative is located in the direction of a PM, the better it is on that PM. If it is located in the opposite direction means that the alternative is performing below average on that PM.

The orientation of the *pi* decision axis identifies the kind of compromise solution that corresponds to the assigned PM weights. The best alternative in terms of the PM evaluations and the weights is usually located in the direction of *pi* axis, but farthest away from the origin. When the weights are changed (in sensitivity analysis), the decision axis is automatically updated to reflect the new compromise. It can be seen from Figure 5.1, Site 2 is located in the direction of *pi* axis, but farthest away from the origin, assuring that Site 2 is the best compromising solution.

The sensitivity and robustness of the results to the variation of PM weights can be observed from the following special features offered in *Decision Lab 2000* (Visual Decision 2003):

1. **Walking Weights** - This display allows the modifications of any PM weight (by moving a pointer located at the bottom of the window) and the observation of the resulting modification of the PROMETHEE II ranking (in terms of net preference flows of the alternatives). The 'Walking Weights' window for the tutorial example is included in Figure 5.1. Any PM could be chosen from a drop-down list given in the middle of the window (in the example it is set for 'Investment').

2. **Stability Intervals (of weights)** - For each PM, a stability interval indicates within which bounds the weights of that PM can be modified without affecting the PROMETHEE II ranking (to a stated stability level), provided that the relative weights of the other PMs are not modified. The 'Stability Intervals' window for tutorial example is given in Figure 5.1. It suggests that in this problem, the weights of PMs could be varied from 46% (in operations cost) to as much as 100% (in environmental impact and social impact).

5.3.4 GAIA-Scenario Plane

In a collective (or group) decision making situation, a particularly useful facility in *Decision Lab 2000* is the multi-scenario analysis, which could take different uncertain conditions (scenarios) together into consideration. For the case study example, which will be discussed later in Section 5.4, the scenarios considered were the actors (or individual members of the DMG) with different preferences (e.g. one scenario could be the PM values combined with RM1's preference parameters).

In a similar manner as to how GAIA-criteria plane is displayed for PM weights, the GAIA-scenario plane displays the properties P1 to P6 above for different scenarios instead of different PMs. The voices of the scenarios could be varied by assigning appropriate weights to the different scenarios. Hence, as discussed in Section 5.2, various DM preferences in a decision problem could be introduced into the analysis in the form of scenarios with appropriate weights assigned to them.

By selecting ‘All Scenarios’ in the GAIA Plane window, the multi-scenario capabilities of *Decision Lab 2000* can be accessed for a joint analysis of different view points as follows (Geldermann and Zhang 2001):

- The multi-scenario PROMETHEE I & II rankings are obtained by considering all the scenarios and their weights.
- The ‘Profiles’ of alternatives are given in terms of scenarios instead of the PMs, and the ‘Stability Intervals’ are computed with respect to the weights of the scenarios (i.e. weights assigned to various actors in the case study example).
- The ‘Walking Weights’ display allows the user to observe the impact of the weights of the scenarios on the multi-scenario PROMETHEE II ranking.
- The ‘Multiple Comparison’ display (applicable only to multi-scenario analysis) allows the user to compare the PROMETHEE II ranking of alternatives in terms of two scenarios.
- Similar to the single scenario case, in the GAIA-criteria plane, each criterion axis represents a weighted aggregate of the different scenarios of that criterion and in the GAIA-scenario plane, each scenario axis represents one scenario.

In a group decision context (PROMETHEE GDSS explained in Section 2.7.3), the GAIA-scenario plane is useful in identifying coalitions of DMs as well as the origin of conflicts among the DMs.

The orientation of the scenario axes roughly indicates which group members are in agreement with each other (when axes point in similar directions) and which group members are in conflict with each other (when axes point in opposite directions). These details related to the case study example are discussed in Section 5.4.2.

5.4 Case Study - Derivation, Sensitivity Analysis, Robustness Measures, and Optimum Operating Rules for Melbourne Water Supply System

As previously outlined in Section 4.3, the potential stakeholders considered for the case study are Resource Managers (RMs), Water Users (WUs) and Environmentalists (ENs). Using the capabilities of the PROMETHEE GDSS (Section 2.7.2) and *Decision Lab 2000* software, the optimum operating rules for the Melbourne water supply system were derived in terms of PM evaluations (Table 3.6) and the stakeholder preference parameters (Tables 4.3, 4.12 and 4.13).

5.4.1 Individual and Group Decision Making Scenarios

As stated in Section 5.3, *Decision Lab 2000* provides the notion of scenarios to offer group decision support through the use of multi-scenario analysis. Several scenarios can be defined within a single Decision Lab document related to an application. They only share the names and the characteristics of the alternatives and PMs. All other data, i.e. evaluations and preference parameters can be different from one scenario to another. Each individual DM could be considered as a separate scenario, and a 'weighting factor' assigned to each of the DMs could prescribe the strength of his/her voice in a final collective decision (Visual Decision 2003).

To acquire a general understanding of the problem, before proceeding to the GDM situations, it was first decided to examine the *Decision Lab 2000* output results for all possible single DM situations. The observed results included the preference flows (Φ^+, Φ^- and Φ), final PROMETHEE rankings, GAIA-criteria plane and 'walking weights' display for each DM. In addition, an 'All DM' group case was also examined in order to understand the extent of influence that the individual RM preferences could make on a collective decision. The results of this particular GDM case were especially useful in:

1. Identifying the most influential RMs in a group decision-making event, and
2. Deciding, which RMs to be included in the groups, (when varying numbers of RMs participate in the group) to represent a collective RMs' view.

Therefore, arising out of the above decision situations, the decision analysis was carried out under all possible single DM situations (8 cases) and one group situation with all six RMs in a group (1 case) as given below:

- Six cases (one case each) with each individual RM (RM1, RM2, RM3, RM4, RM5 and RM6) preferences,
- One case with single representative Environmentalist (EN_{rep}) preferences,
- One case with single representative Water User (WU_{rep}) preferences, and
- One case with all six RMs' preferences together in a group situation.

Based on the individual DM preferences given in Section 4.5.3, the PROMETHEE II rankings were obtained for all these nine cases. From the 'All RMs' scenario, it is possible to observe the collective decision of all six RMs together in a group, which is a compromise of their individual preferences. Illustrative examples of PROMETHEE 1 and PROMETHEE II rankings for RM1 are given in Figures 5.2 and 5.3 respectively. The positive flows (Φ^+), negative flows (Φ^-) and net preference flows (Φ) for all nine cases are given in Table 5.2.

Single DM Case: GAIA-Criteria Plane

GAIA-criteria plane for a single DM case (RM1) is illustrated in Figure 5.4, yielding a sufficiently high Δ value of 98.02% and a moderately long *pi* axis. Therefore, if RM1 is considered to be the only DM, the information rendered in Figure 5.3 could be used to arrive at a decision with reasonable accuracy. Alternative operating rules are denoted by solid triangles and various other shapes denote eight PMs with their identification names.

There are two distinctive clusters of alternatives i.e. (OPR1, OPR3, OPR5, OPR7, OPR9, OPR11, OPR13, OPR15) and (OPR2, OPR4, OPR6, OPR8, OPR10, OPR12, OPR14, OPR16). Also the OPR7 is located farthest away from the origin in the direction of *pi* axis, confirming the results of PROMETHEE rankings (Figures 5.1 and 5.2) that, OPR7 is the optimum operating rule in relation to RM1's preferences. More details of the properties of a decision problem that can be deduced from P1:P6 of a GAIA-criteria plane (detailed in Section 5.3.3) will be discussed later in Section 5.4.2, in relation to two decision-making groups.

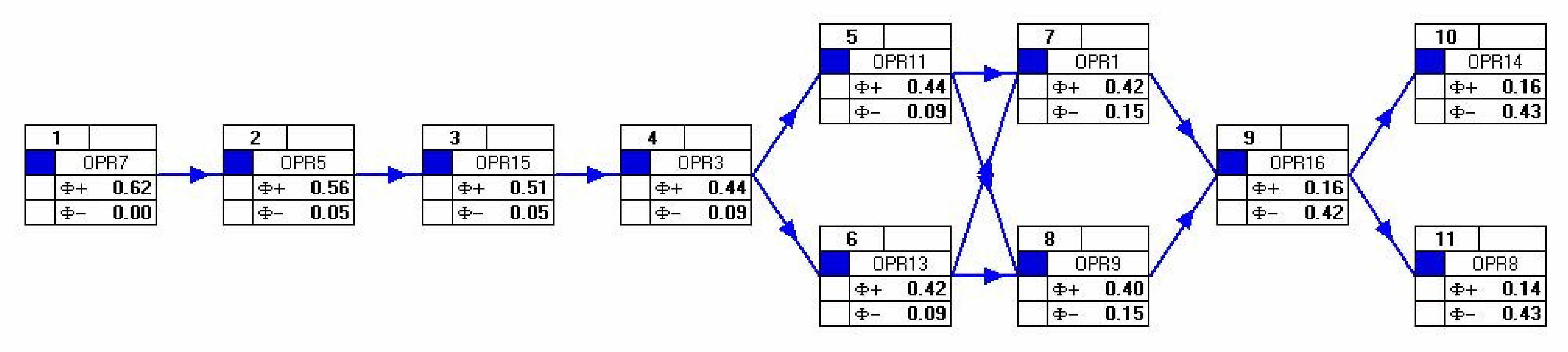


Figure 5.2: PROMETHEE I Ranking of Alternative Operating Rules based on RM1's Preferences

(Note: only 11 rank positions are shown for clarity)

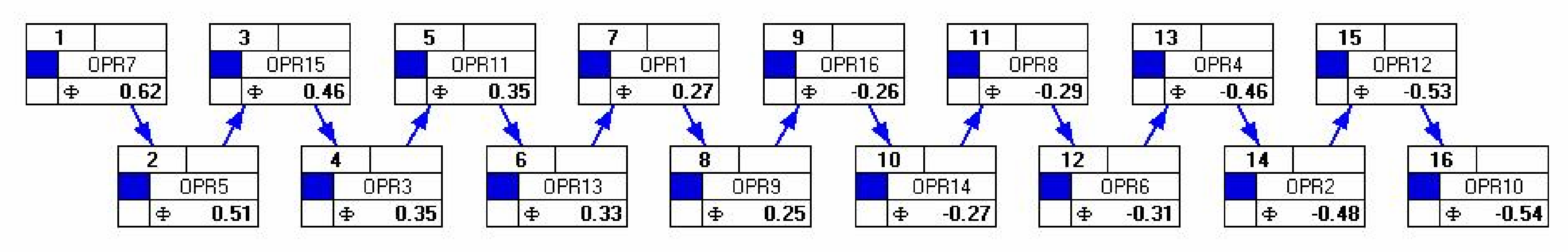


Figure 5.3: PROMETHEE II Ranking of Alternative Operating Rules based on RM1's Preferences

Table 5.2: Positive Flows, Negative Flows and Net Preference Flows for Nine Possible Single DM Cases

Operating Rule	RM1			RM2			RM3			RM4			RM5			RM6		
	Φ^+	Φ^-	Φ	Φ^+	Φ^-	Φ	Φ^+	Φ^-	Φ	Φ^+	Φ^-	Φ	Φ^+	Φ^-	Φ	Φ^+	Φ^-	Φ
OPR 1	0.42	0.15	0.27	0.15	0.18	-0.03	0.35	0.02	0.33	0.25	0.18	0.07	0.44	0.11	0.32	0.28	0.18	0.10
OPR 2	0.05	0.53	-0.48	0.24	0.19	0.05	0.03	0.43	-0.40	0.02	0.43	-0.40	0.10	0.50	-0.40	0.02	0.46	-0.44
OPR 3	0.44	0.09	0.35	0.16	0.18	-0.02	0.39	0.02	0.37	0.30	0.09	0.21	0.47	0.04	0.43	0.36	0.11	0.25
OPR 4	0.06	0.52	-0.46	0.24	0.18	0.06	0.03	0.43	-0.40	0.02	0.42	-0.40	0.11	0.48	-0.37	0.04	0.44	-0.39
OPR 5	0.56	0.05	0.51	0.17	0.23	-0.06	0.43	0.01	0.41	0.28	0.12	0.16	0.44	0.16	0.28	0.36	0.13	0.24
OPR 6	0.13	0.44	-0.31	0.21	0.22	-0.01	0.03	0.39	-0.35	0.06	0.35	-0.28	0.06	0.51	-0.45	0.09	0.41	-0.32
OPR 7	0.62	0.00	0.62	0.20	0.23	-0.04	0.43	0.01	0.42	0.41	0.03	0.38	0.55	0.08	0.47	0.47	0.03	0.44
OPR 8	0.14	0.43	-0.29	0.19	0.24	-0.04	0.03	0.39	-0.35	0.07	0.34	-0.27	0.10	0.49	-0.39	0.11	0.38	-0.27
OPR 9	0.40	0.15	0.25	0.23	0.17	0.06	0.38	0.03	0.35	0.27	0.13	0.13	0.45	0.08	0.37	0.31	0.17	0.14
OPR 10	0.04	0.57	-0.54	0.25	0.18	0.07	0.02	0.43	-0.41	0.11	0.31	-0.20	0.12	0.52	-0.39	0.10	0.39	-0.29
OPR 11	0.44	0.09	0.35	0.17	0.18	-0.02	0.38	0.03	0.36	0.35	0.05	0.29	0.50	0.02	0.48	0.41	0.06	0.35
OPR 12	0.04	0.57	-0.53	0.25	0.18	0.07	0.02	0.43	-0.41	0.11	0.31	-0.20	0.16	0.50	-0.34	0.10	0.39	-0.29
OPR 13	0.42	0.09	0.33	0.16	0.18	-0.02	0.38	0.03	0.36	0.31	0.07	0.24	0.40	0.13	0.27	0.38	0.08	0.30
OPR 14	0.16	0.43	-0.27	0.20	0.18	0.02	0.06	0.37	-0.31	0.19	0.26	-0.07	0.11	0.47	-0.36	0.17	0.31	-0.14
OPR 15	0.51	0.05	0.46	0.13	0.25	-0.12	0.39	0.02	0.36	0.43	0.02	0.41	0.48	0.08	0.40	0.46	0.01	0.45
OPR 16	0.16	0.42	-0.26	0.20	0.18	0.02	0.06	0.37	-0.31	0.19	0.26	-0.07	0.13	0.45	-0.32	0.20	0.29	-0.09

Operating Rule	EN_{rep}			WU_{rep}			All RMs		
	Φ^+	Φ^+	Φ	Φ^+	Φ^+	Φ	Φ^+	Φ^-	Φ
OPR 1	0.00	0.00	0.00	0.20	0.11	0.08	0.35	0.02	0.33
OPR 2	0.00	0.00	0.00	0.02	0.30	-0.28	0.03	0.43	-0.40
OPR 3	0.00	0.00	0.00	0.22	0.05	0.17	0.39	0.02	0.37
OPR 4	0.00	0.00	0.00	0.02	0.30	-0.28	0.03	0.43	-0.40
OPR 5	0.00	0.00	0.00	0.21	0.07	0.13	0.43	0.01	0.41
OPR 6	0.00	0.00	0.00	0.03	0.25	-0.21	0.03	0.39	-0.35
OPR 7	0.00	0.00	0.00	0.27	0.03	0.25	0.43	0.01	0.42
OPR 8	0.00	0.00	0.00	0.04	0.24	-0.21	0.03	0.39	-0.35
OPR 9	0.00	0.00	0.00	0.20	0.08	0.13	0.38	0.03	0.35
OPR 10	0.00	0.00	0.00	0.07	0.22	-0.15	0.02	0.43	-0.41
OPR 11	0.00	0.00	0.00	0.24	0.03	0.21	0.38	0.03	0.36
OPR 12	0.00	0.00	0.00	0.07	0.22	-0.15	0.02	0.43	-0.41
OPR 13	0.00	0.00	0.00	0.22	0.04	0.18	0.38	0.03	0.36
OPR 14	0.00	0.00	0.00	0.12	0.20	-0.08	0.06	0.37	-0.31
OPR 15	0.00	0.00	0.00	0.30	0.02	0.28	0.39	0.02	0.36
OPR 16	0.00	0.00	0.00	0.12	0.20	-0.08	0.06	0.37	-0.31

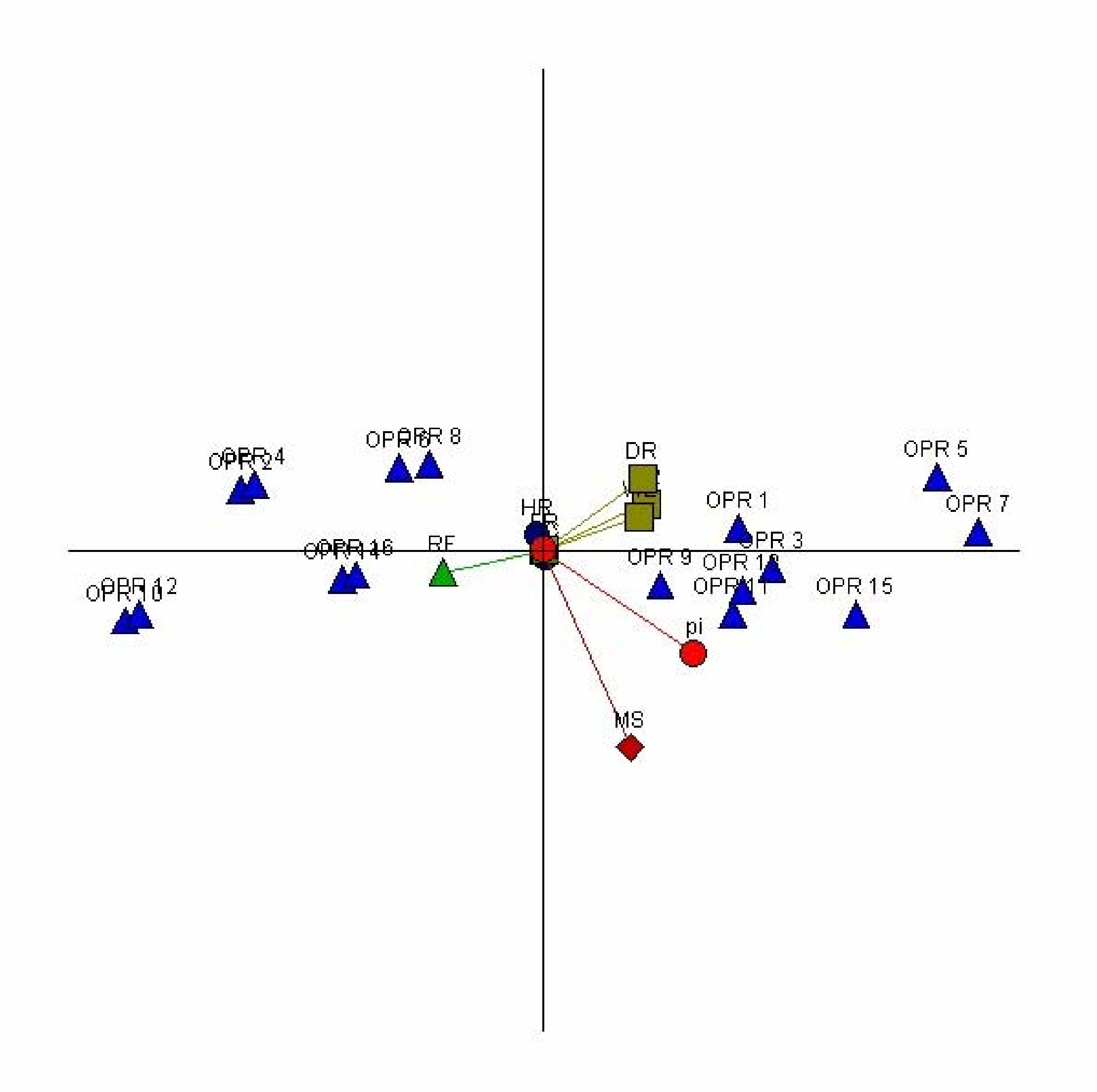


Figure 5.4: GAIA-Criteria Plane for a Single DM Case - RM1 (Δ = 98.02%)

Single DM Case: Walking Weights Display

For single DM cases, the *Decision Lab 2000* 'Walking Weights' screen display includes two charts for each DM, allowing the DM to understand the effect of his/her PM weights on the final ranking of alternatives judged in terms of the net preference flows. A sample screen display (for RM1) is given in Figure 5.5. The top chart is the graphical display of the net preference flows of alternative operating rules (*y*-axis) according to RM1's preferences. The bottom chart gives the PM weights given by RM1. However, by moving the pointer at the bottom of the screen allows observing the variations in net preference flows with respect to any selected PM (in this case it is set for Supply reliability - SR). By having the tallest bar in the top graph, OPR7 could be judged as the optimum operating rule according to RM1's preferences.

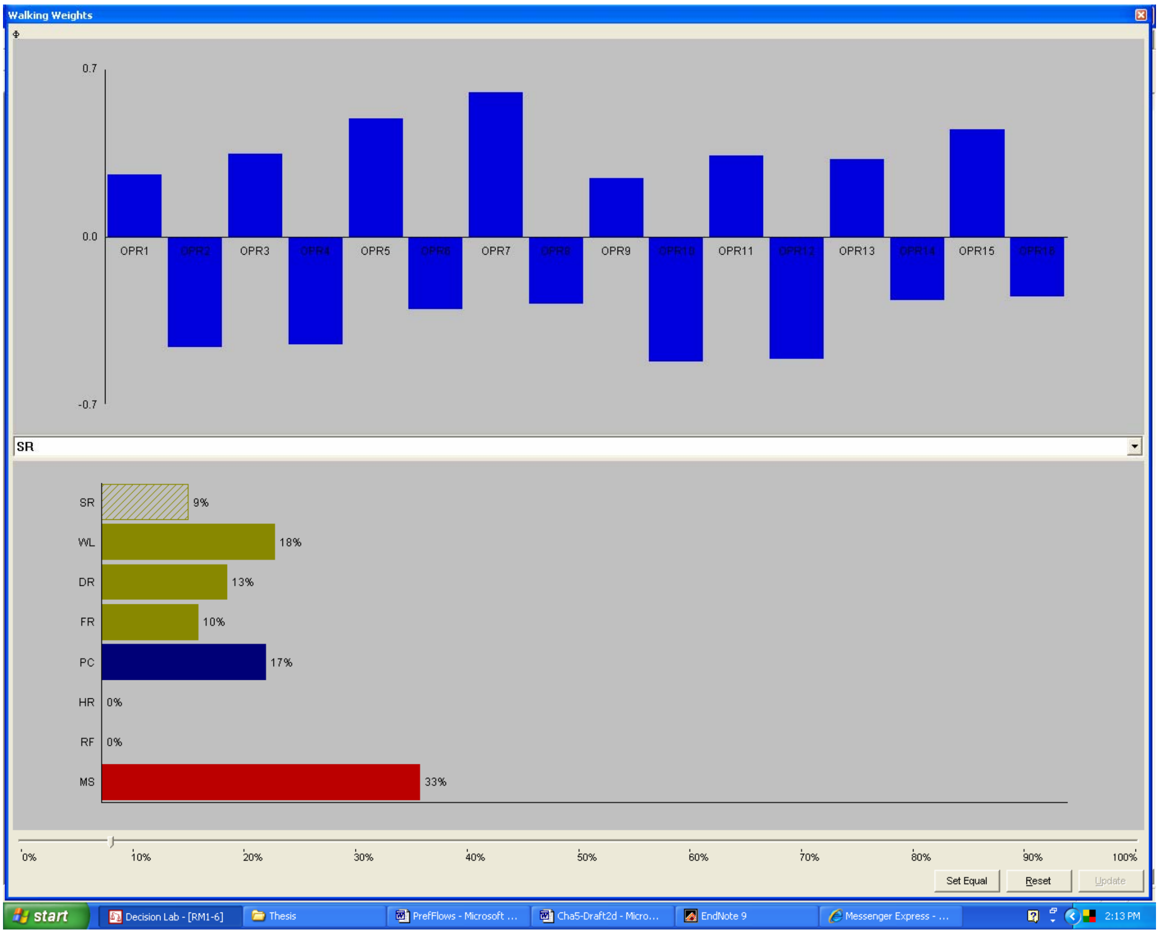


Figure 5.5: Net Preference Flows of the Alternative Operating Rules and the Weights of PMs - Single DM Case (RM1)

Group Decision-Making Case: GAIA-Criteria Plane

The GAIA-criteria plane for GDM case (‘All RMs’) is illustrated in Figure 5.6, also yielding a sufficiently high Δ value of 98.68% and a fairly long *pi* axis. Therefore, if all six RMs form a group to make collective decisions, the information given in Figure 5.6 could be used to arrive at a decision with reasonable accuracy. The two distinctive clusters of alternatives i.e. (OPR1, OPR3, OPR5, OPR7, OPR9, OPR11, OPR13, OPR15) and (OPR2, OPR4, OPR6, OPR8, OPR10, OPR12, OPR14, OPR16) are also visible in here. Also in this case, the OPR7 is located farthest away from the origin in the direction of *pi* axis, suggesting that, OPR7 is the optimum operating rule in relation to all six RMs’ collective preferences.

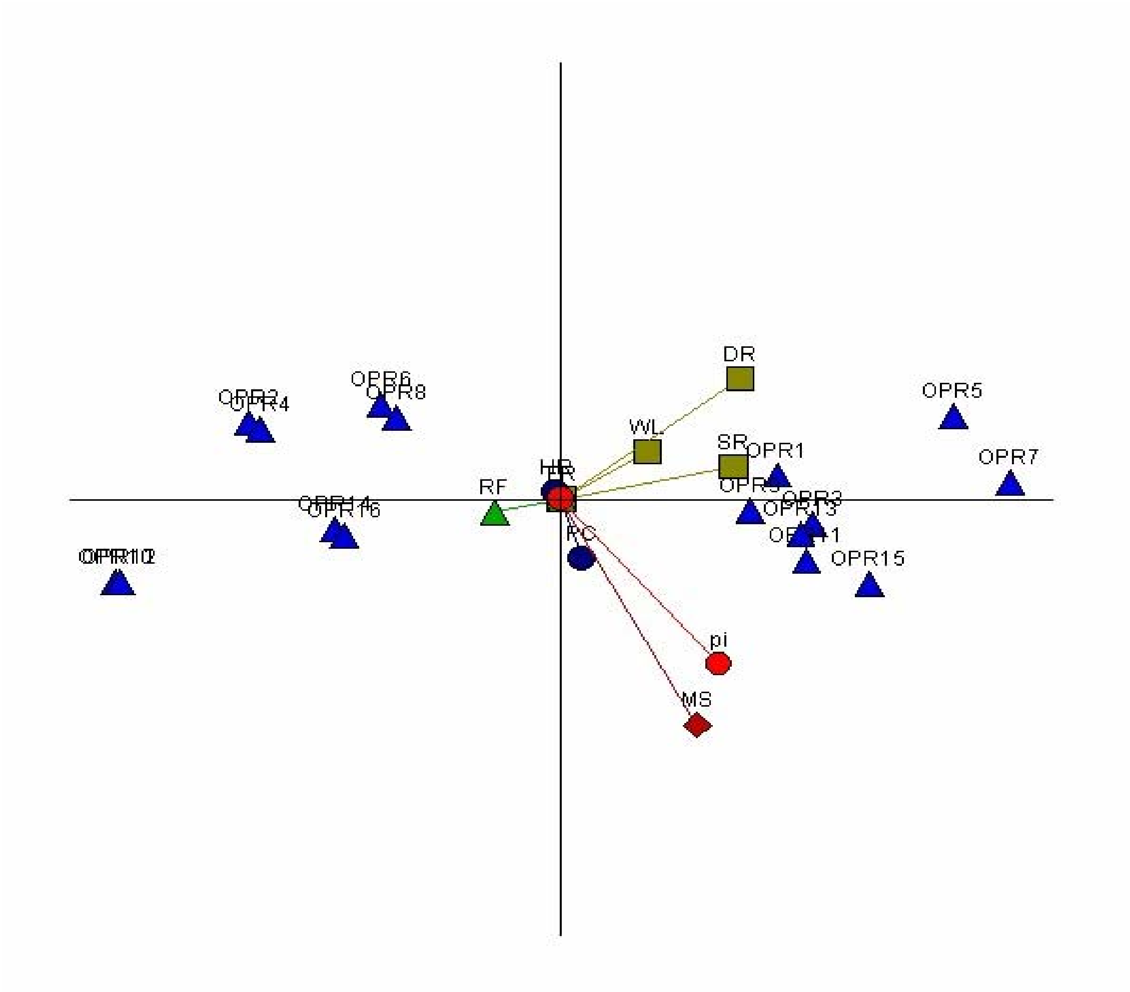


Figure 5.6: GAIA-Criteria Plane for a Group Decision-Making Case (‘All RMs’)
(Δ = 98.68%)

Group Decision-Making Case: GAIA-Scenario Plane

The GAIA-scenario plane for group decision-making case (‘All RMs’) is illustrated in Figure 5.7, yielding a sufficiently high Δ value of 98.51% and a long *pi* axis. Similar to above RM1’s case, the two distinctive clusters of alternatives are apparent with OPR7 showing up as the optimum operating rule in relation to the collective preferences of all six RMs. It is also noted that RM1’s preferences match closely with the collective decision of all RMs’, followed by RM3 and RM5; a pair of RMs having similar preferences. Though RM4 and RM6 also had similar preferences, they appear to be conflicting with RM2’s preferences. However, RM2 did not have sufficient powers to discriminate the alternatives since the RM2’s scenario axis was comparatively short (Figure 5.7).

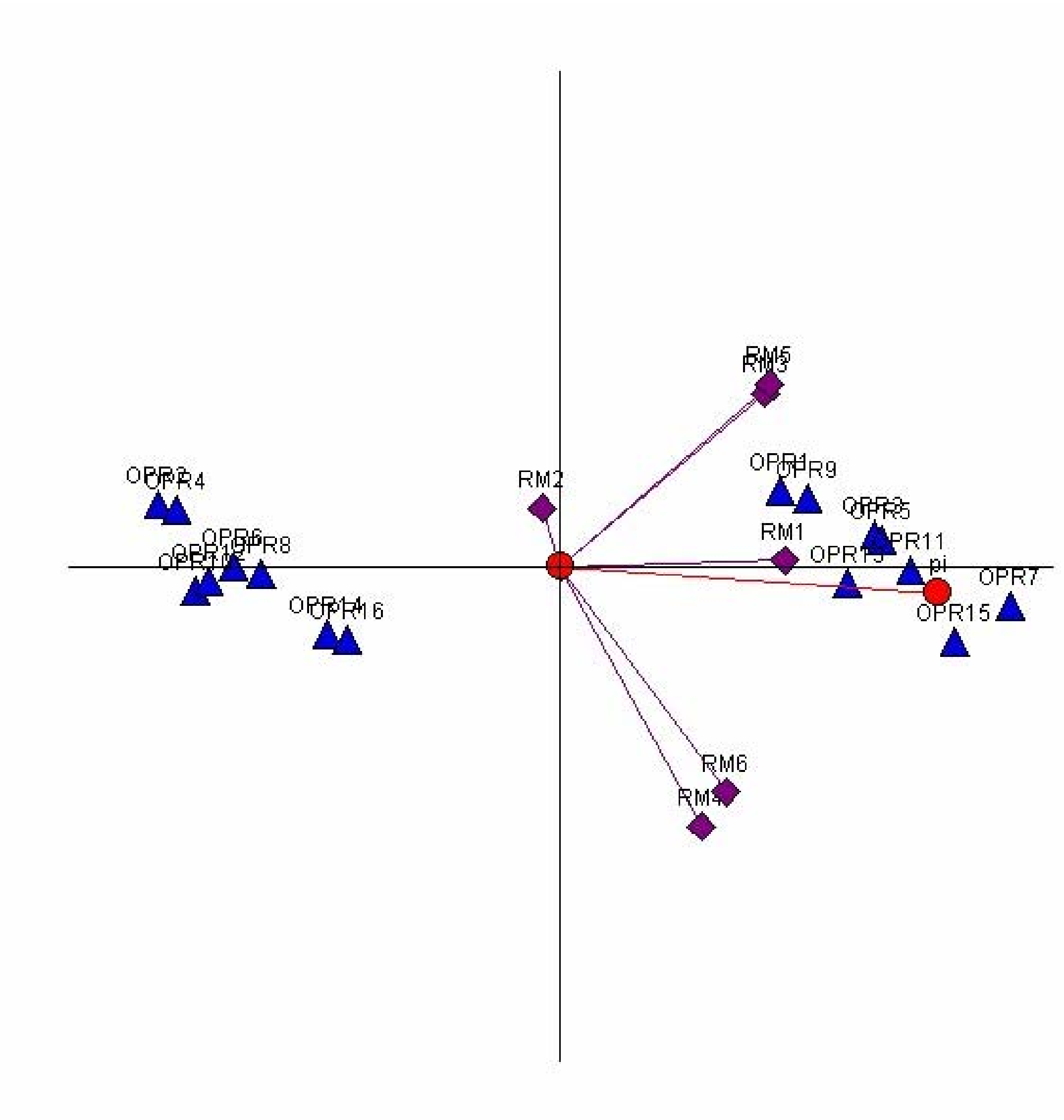


Figure 5.7: GAIA-Scenario Plane for a Group Decision-Making Case ('All RMs') ($\Delta = 98.51\%$)

Group Decision-Making Case: Walking Weights Display

The 'walking weights' display for group decision-making case 'All RMs' is given in Figure 5.8. The top chart gives the net preference flows of the alternative operating rules for all six RMs together. Instead of PM weights as in the case of single DM case, the bottom chart (in this case) indicates the weights assigned for the voice of each RM in the group. When RMs are assigned equal weights (i.e. 17% each) in 'All RMs' case, OPR7 is indicated as the optimum operating rule, possessing the tallest bar in the top graph in Figure 5.8.

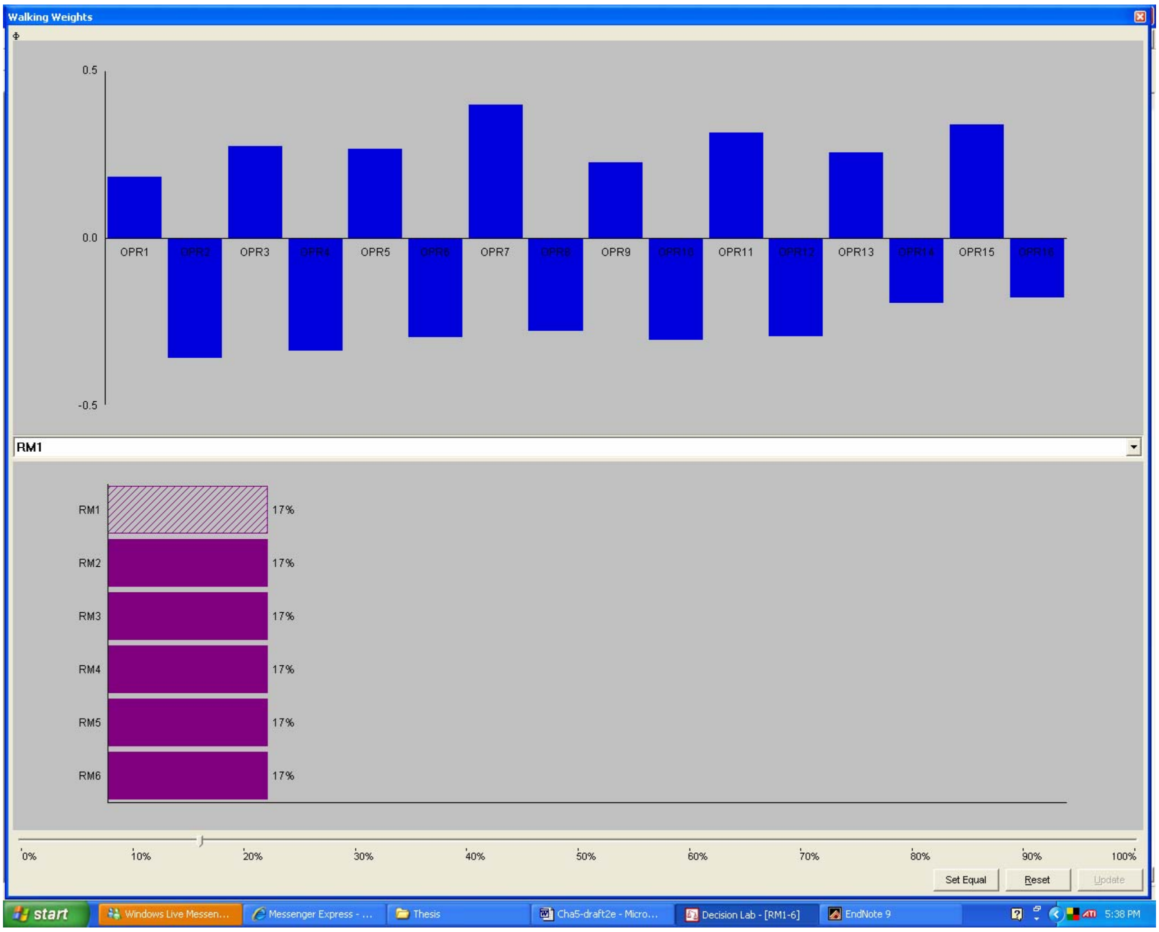


Figure 5.8: Net Preference Flows of the Alternative Operating Rules and the Weights of Decision Makers - ‘All RMs’ Case

PROMETHEE II Rankings

The PROMETHEE II rankings for the 16 alternative operating rules obtained for 8 single DM cases and the ‘All RMs’ group case are summarised in Table. 5.3. As shown in Table 5.3, two RMs, RM1 and RM3, placed the OPR7 in the highest rank position and another three RMs, i.e. RM4, RM5 and RM6 and WU_{rep} placed OPR7 in the second highest rank position. Also in a collective judgement by all the RMs, OPR7 is the highest-ranking alternative among all 16 operating rules.

The ranking for EN_{rep} indicated that all operating rules are equally best, the reason for this being ENs’ preferences having large thresholds (large *p* & *q* values), which stretch beyond the boundaries of the variations observed in the PM values given in the decision matrix (Table 2.1). According to the PROMETHEE methodology discussed in Section 2.7.2, in the event of the preference thresholds being set outside the variation region of any PMs (observed by the decision matrix values), the contribution to the net preference flow by that PM becomes zero, irrespective of the value of PM weight.

Table 5.3: PROMETHEE II Complete Rankings of Operating Rules for Different Individual DM Cases and 'All RMs' Group Case

Rank	Single Decision Maker (DM) Scenario								Group Scenario
	RM1	RM2	RM3	RM4	RM5	RM6	EN$_{rep}$	WU$_{rep}$	All 6 RMs
Rank 1	7	10,12	7	15	11	15	All operating rules are equally ranked	15	**7**
Rank 2	5	_	5	7	7	7		7	**15**
Rank 3	15	4	3	11	3	11		11	**11**
Rank 4	3	9	15	13	15	13		13	**3**
Rank 5	11	2	13	3	9	3		3	5
Rank 6	13	16	11	5	1	5		5	13
Rank 7	1	14	9	9	5	9		9	9
Rank 8	9	6	1	1	13	1		1	1
Rank 9	16	11	16	16	16	16		16	16
Rank 10	14	13	14	14	12	14		14	14
Rank 11	8	3	6	10	14	8		10,12	8
Rank 12	6	1	8	12	4	10,12		_	12
Rank 13	4	7	4	8	8	_		8	6
Rank 14	2	8	2	6	10	6		6	10
Rank 15	12	5	12	4	2	4		4	4
Rank 16	10	15	10	2	6	2		2	2

In order to identify the most influential RMs in a GDM event, only the first four rank positions for all six RMs were analysed in detail. As shown shaded in Table 5.3, the first four highest ranked alternatives, in the order of their rank positions are OPR7, OPR15, OPR11 and OPR3. The contribution made by each RM on the net preference flows (Φ) of the four highest-ranked operating rules is given in Table 5.4.

The DMG could comprise single, several or all RMs, or it could comprise a combination of RMs, ENs and WUs. In forming a group comprising several RMs, the RM who contributed most for the net preference flow of the first four ranked options (in the 'All RMs' group case) were considered, in the order of magnitude of their contribution to the net preference flow. Hence, as shown in Table 5.4, this order will be RM1, RM5, RM3, RM6, RM4 and RM2. For a given decision making situation, the DM group could be formed by incorporating pre-decided stakeholder representation in the group. However, it is also important to examine the output results for various combinations of stakeholder representations within the DM group. In the event of more than one representation from any of these DMs in a group, the appropriate weights assigned to scenarios (as in *Decision Lab 2000*) could prescribe the required representations.

Table 5.4: Net preference Flows (Φ) contributed by each RM on the First Four Highest-Ranked Operating Rules

Resource Manager	OPR 7	OPR 15	OPR 11	OPR 3	Total net preference flow (? Φ)	Order of RMs contribution to the 4 highest-ranked operating rules
RM1	0.6206	0.4589	0.3457	0.3549	1.7801	1 (contributed most)
RM2	-0.0366	-0.1175	-0.0155	-0.0221	-0.1917	6 (contributed least)
RM3	0.4167	0.3649	0.3554	0.3665	1.5035	3
RM4	0.3811	0.4092	0.2949	0.2085	1.2937	5
RM5	0.4680	0.3980	0.4833	0.4260	1.7753	2
RM6	0.4436	0.4462	0.3459	0.2455	1.4812	4

In the case study, first the rankings and the results were analysed with two hypothetical group decision-making situations, each with 6 representations (actors) and then the sensitivity and robustness of results were observed due to varying group compositions in terms of the number RMs in the group. The analyses are discussed in Section 5.4.2. The two groups considered were as follows:

- Group 1 - with 3RMs (RM1, RM5 & RM3), 2WUs and 1EN
- Group 2 - with 4RMs (RM1, RM5, RM3 & RM6), 1WU and 1EN

5.4.2 Decision Analysis Results

The following sections present the results of the decision analysis, using *Decision Lab 2000* for the two groups defined in the previous section.

5.4.2.1 Group 1 Results

PROMETHEE I and PROMETHEE II rankings obtained for Group 1 are given in Figures 5.9 and 5.10 respectively. These rankings sort the best operating rules from the worst, taking all the actors' preferences into account. As discussed earlier in Section 5.3, PROMETHEE I partial ranking is based on strongly established (no compensations, but with incomparabilities) preferences only and PROMETHEE II complete ranking is based on a numerical rating of the alternatives from the best alternative to the worst alternative leaving no incomparable pair of alternatives.

PROMETHEE I partial ranking in Figure 5.9 clearly shows that OPR7 is the best alternative and OPR15 is the second best alternative in relation to the preferences of Group 1. However, it is also seen that the third best alternative is less obvious, since there are two sets of incomparable alternatives, (OPR5) and (OPR11, OPR3, OPR13), lined-up next, which outrank all other alternatives except for OPR7 and OPR15. This ambiguity is not apparent in PROMETHEE II complete ranking given in Figure 5.10.

GAIA-criteria plane for Group 1 is illustrated in Figure 5.11 with a Δ value of 98.65%. Since the *pi* decision axis is considerably long in this case, the properties P1:P6 described in Section 5.3 are valid to deduce judgements on the decision problem. OPR7 which is located farthest away in the direction of *pi* decision axis can be considered as the best compromising alternative in this case.

It is observed from Figure 5.11 that there are two distinctive clusters of alternatives, i.e. cluster 1 containing OPR1, OPR3, OPR5, OPR7, OPR9, OPR11, OPR13 & OPR15 and the cluster 2 containing OPR2, OPR4, OPR6, OPR8, OPR10, OPR12, OPR14 & OPR16. The notable character, which differentiates the cluster 1 from cluster 2 and common to all even numbered operating rules in cluster 2, is the increased river flows downstream of Thomson dam. In addition, all cluster 2 alternatives being placed in opposite direction to the *pi* decision axis can be categorised as weakly performing alternatives in relation to the stakeholder preferences.

For the 16 alternative operating rules considered in this case study, both Frequency of restrictions (FR) and Hydropower revenue (HR) seem to have no differentiating power, since their projections on the GAIA plane is very short, meaning those two axes are almost orthogonal to the GAIA plane. In contrast, the Minimum reservoir storages (MS) emerged to be the most influential PM with the highest differentiating power.

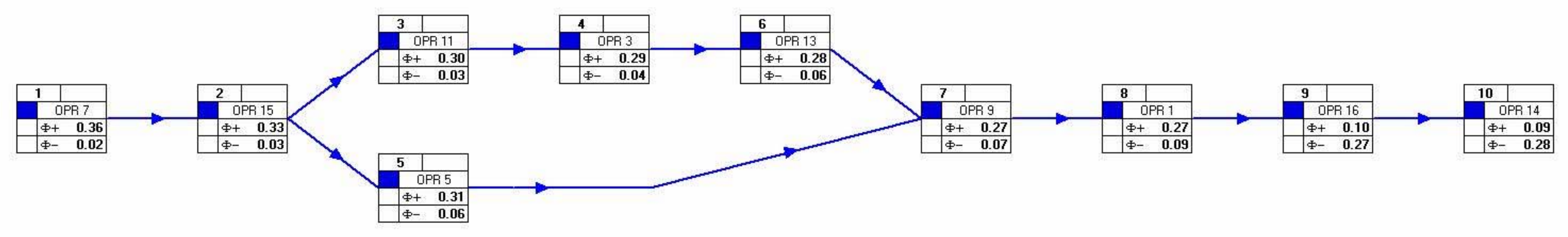


Figure 5.9: PROMETHEE I partial ranking for Group 1

(Note: Only 10 rank positions are shown for clarity)

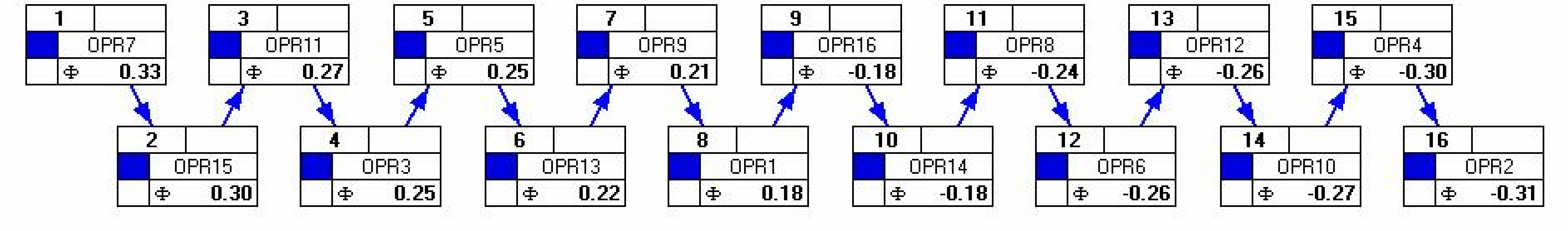


Figure 5.10: PROMETHEE II complete ranking for Group 1

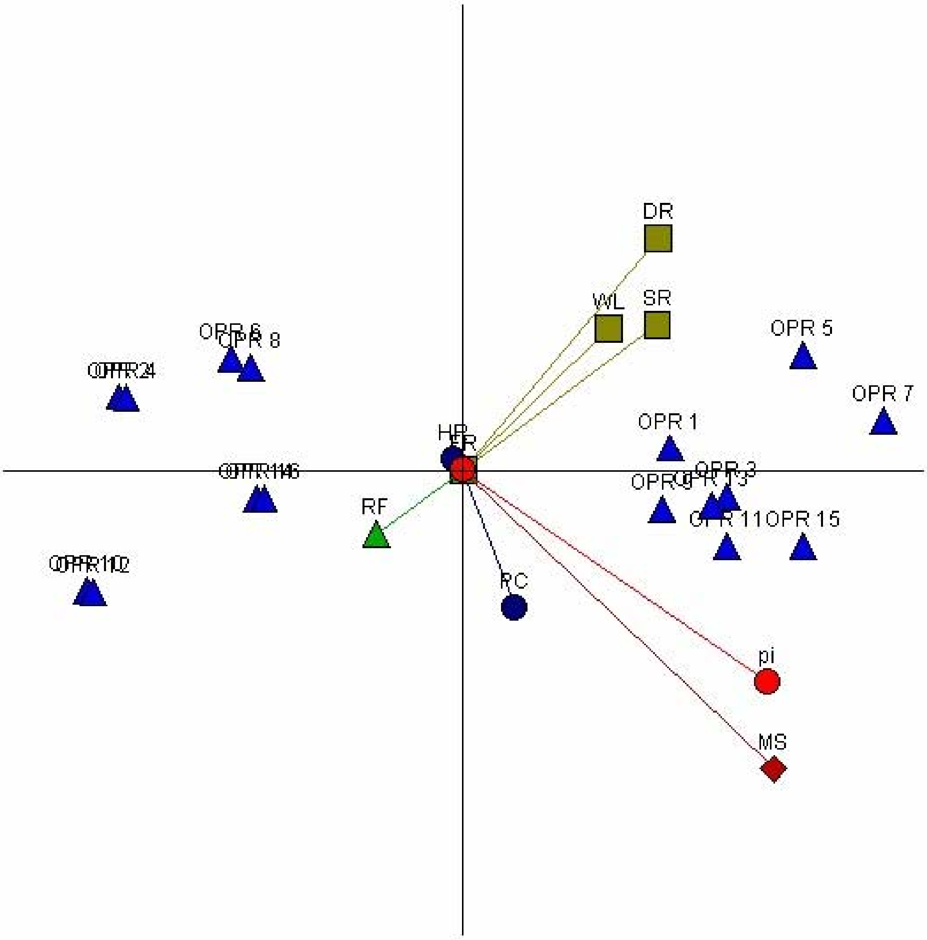


Figure 5.11: GAIA-Criteria Plane for Group 1 (Δ = 98.65%)

Three PM axes Supply reliability (SR), Worst restriction level (WL) and Duration of restrictions (DR), all belonging to the 'Level of Service' category are oriented approximately in the same direction indicating similar preferences. It is also interesting to note that River flows (RF) is strongly conflicting with the above three level of service related PMs, which should be an obvious natural observation. However, the approximately orthogonal axes of (SR, WL, DR) and MS observed in here, which should represent independent groups of PMs, is one unusual phenomena that is difficult to explain in water supply reservoir system operations.

The GAIA-scenario plane for Group 1 illustrated in Figure 5.12 with a Δ value of 99.21% gives similar observations to GAIA-criteria plane (Figure 5.11). In GAIA-scenario plane, the scenario axes represent each of the actors in the group and are denoted by solid diamonds. The length of the scenario axes is indicative of the assurance with which the group view is held. The contributions to the final ranking transpire from RM1, RM5, RM3 and WU in the order of their magnitude. However, EN$_{rep}$'s contribution (referred to as EN in the *Decision Lab 2000* outputs) is negligible in this case. This graph is most useful in identifying the potential conflicts among the various actors in the group though it is directly used to identify the best compromising alternative. Since the scenario axes point approximately in similar directions, this orientation roughly indicates that the actors in the group are in general agreement with each other.

It is also seen that the OPR7 is located in the direction of *pi* decision axis (indicated in red) but farthest from the origin, which is ranked first in both the PROMETHEE I and II rankings. The information deduced from the GAIA-scenario plane in this case could be considered as highly reliable since the Δ value is 99.21% (Figure 5.12).

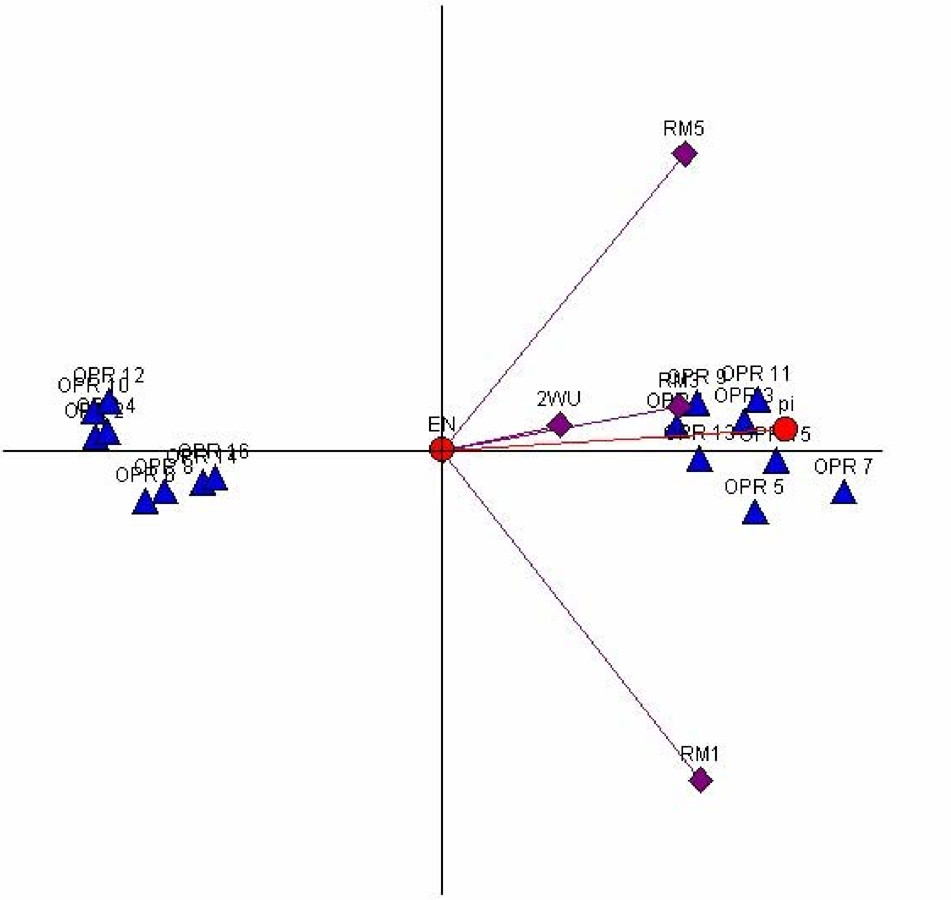


Figure 5.12: GAIA-Scenario Plane for Group 1 (Δ = 99.21%)

The profiles of the alternatives in clusters 1 and 2 are shown in Figures 5.13 and 5.14 respectively, y-axis representing the net preference flow (Φ) contribution for each of the actors in the group. For each DM, these profiles indicate the overall performance of an alternative with respect to the scenarios, *y*-axis representing the net preference flow, Φ.

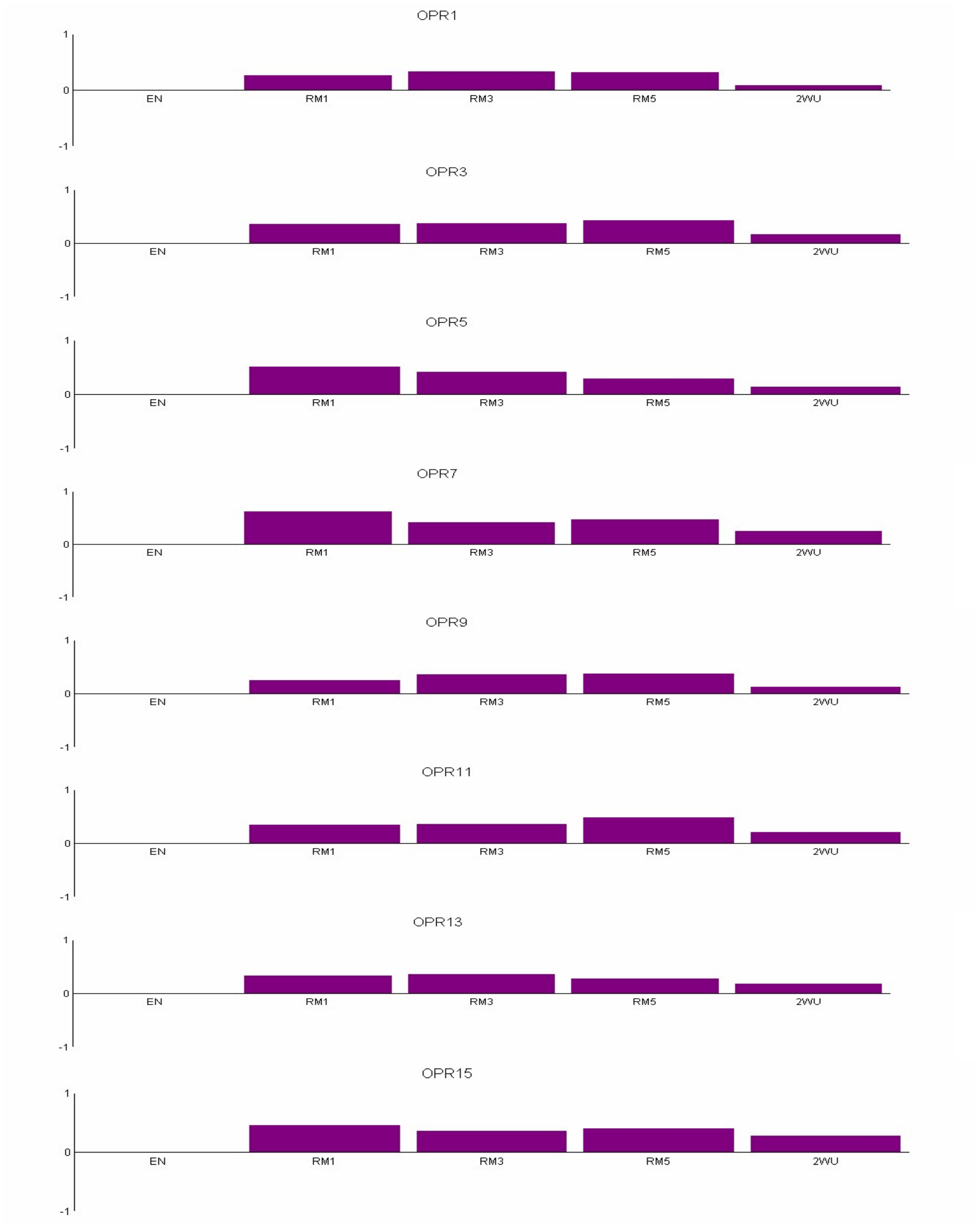


Figure 5.13: Profiles of the Alternative Operating Rules in Cluster 1

The upward bars in cluster 1 alternatives indicate good performance giving positive contributions to Φ, while the downward bars in cluster 2 alternatives indicate poor performance giving negative contributions to Φ.

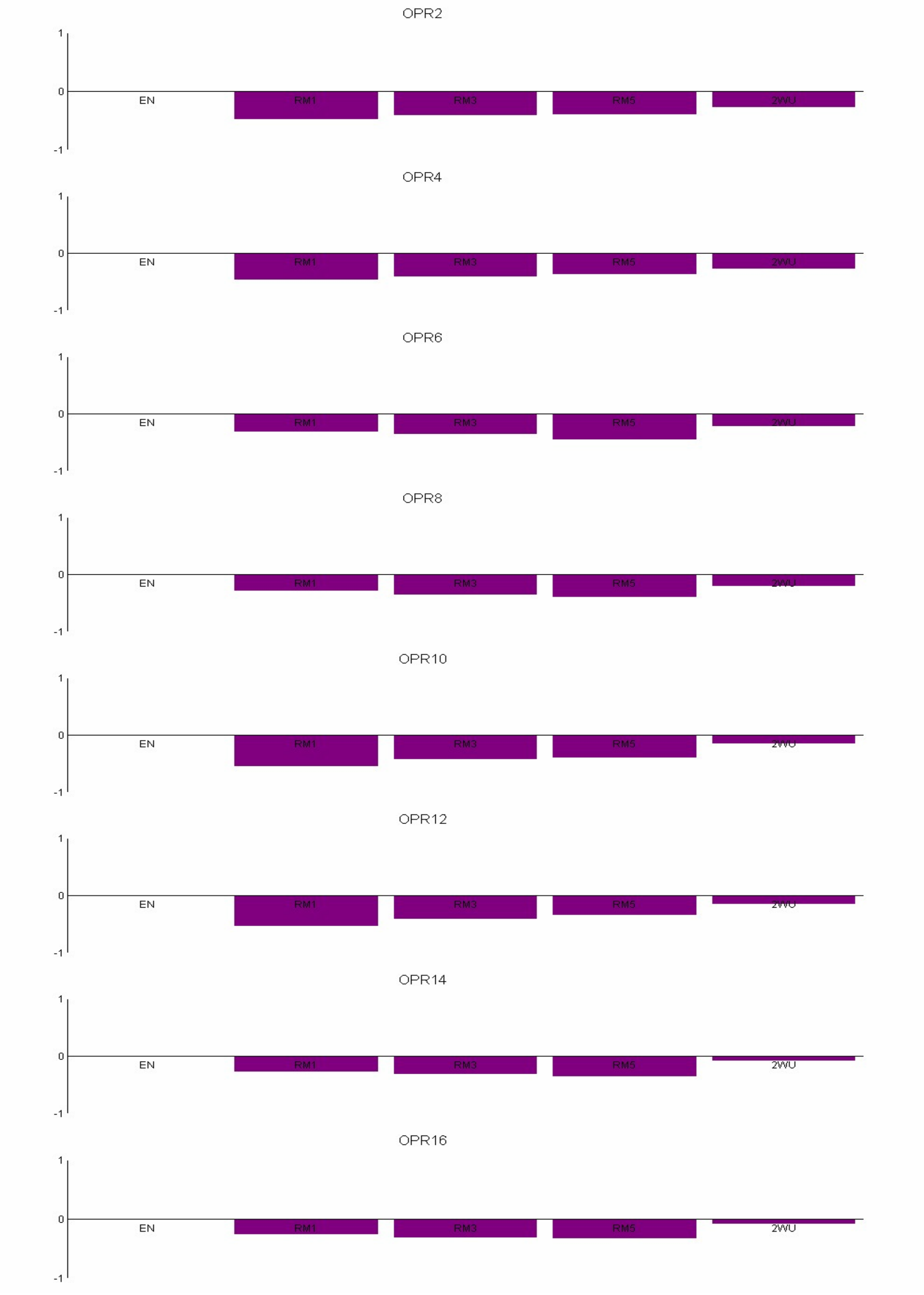


Figure 5.14: Profiles of the Alternative Operating Rules in Cluster 2

It is also evident from Figures 5.12, 5.13 and 5.14, that the preferences of EN_{rep}'s is non-significant, and the preferences of WU_{rep}'s is less significant compared to the preferences of RMs in the group.

5.4.2.2 Group 2 Results

The PROMETHEE I partial ranking and PROMETHEE II complete ranking for Group 2 are shown in Figures 5.15 and 5.16 respectively, similar to Group 1 results discussed in Section 5.4.2.1.

According to Figures 5.15 and 5.16, both PROMETHEE I and PROMETHEE II rankings for Group 2, the best alternative and the second best alternative are clearly distinguished as the OPR7 and OPR15 respectively without any other incomparable alternative. Except for the interchanging of the fourth and fifth rank positions in PROMETHEE II ranking, Group 2 results are very close to Group 1 results that have been discussed above.

The GAIA-criteria plane for Group 2 is given in Figure 5.17. This figure indicates a Δ value of 98.63% and a considerably long *pi* decision axis, yielding quite reliable results. It was also observed that the GAIA-criteria plane of Group 2 was very similar to Group 1 results given in Figure 5.11.

. The GAIA-scenario plane for Group 2 is shown in Figure 5.18 with a Δ value of 98.73% and a considerably long *pi* decision axis. OPR7 is the best alternative in relation to collective preferences of the Group 2 actors.

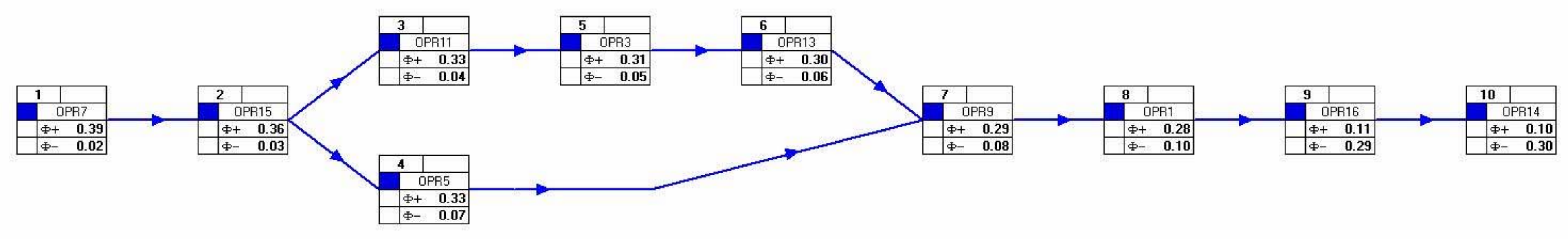


Figure 5.15: PROMETHEE I Partial Ranking for Group 2

(Note: only 10 rank positions are shown for clarity)

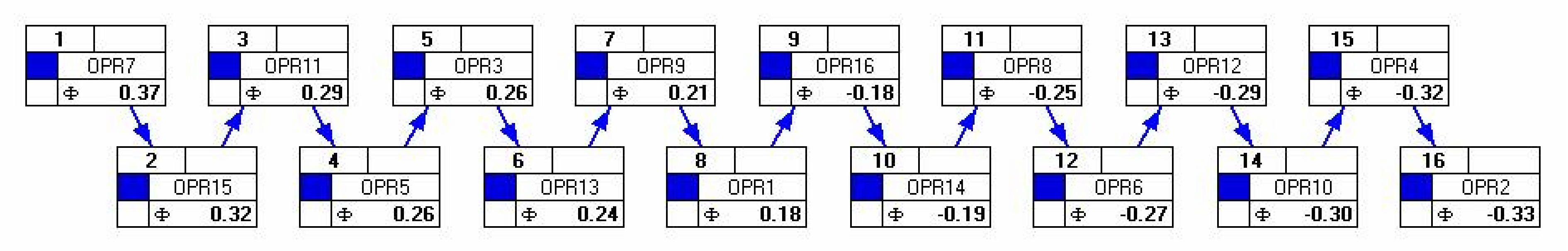


Figure 5.16: PROMETHEE II Complete Ranking for Group 2

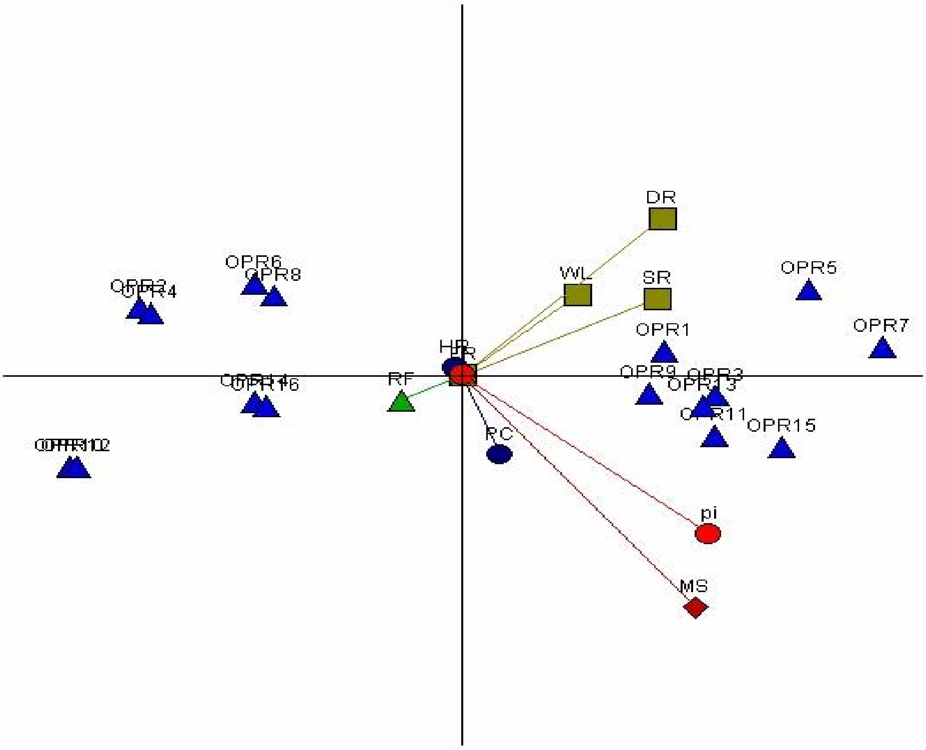


Figure 5.17: GAIA-Criteria Plane for Group 2 (Δ = 98.63%)

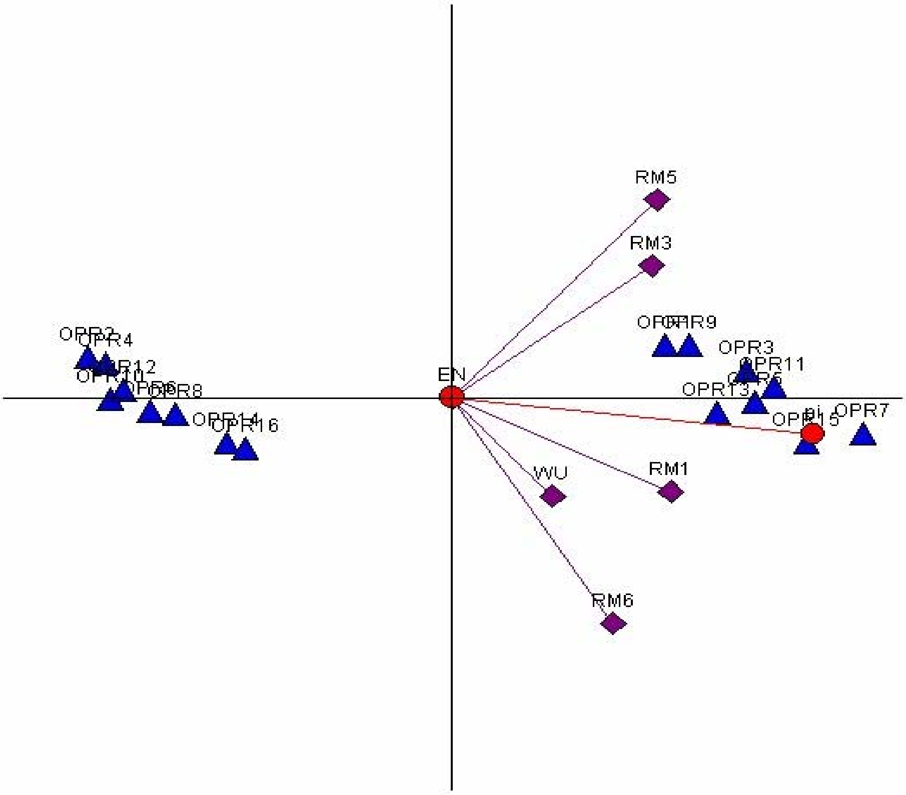


Figure 5.18: GAIA-Scenario Plane for Group 2 (Δ = 98.73%)

The output results discussed above for the 16 operating rules considered in this study provided an insight into the problem and are used as additional information in deriving the optimum operating rules for Melbourne water supply system, which is discussed in Section 5.4.3. The results were derived for Group 1 and Group 2 separately and then the sensitivity of results for varying weights given to the actors in each group is discussed in Section 5.4.4. In Section 5.4.5, the general robustness of the first two highest ranked alternatives were examined against their stability to remain in the first and second rank positions due to varying group compositions and varying weights given to different actors in the group. To achieve reasonable robustness of the results, the stability intervals window of *Decision Lab* 2000 should display significantly large bandwidths for these weight variations.

5.4.3 Optimum Operating Rules for Melbourne Water Supply System

The PROMETHEE II rankings of the alternative operating rules derived from the *Decision Lab 2000* software with their net preference flows for Group 1 and Group 2 are shown in Table 5.5.

Table 5.5: Rankings and Preference Flows of Operating Rules for Two DMGs

Rank	Group 1 - 3 RMs (RM1,RM5 & RM3) +2WUs+EN				Group 2 - 4RMs (RM1, RM5, RM3 & RM6) +WU+EN			
	Operating Rule	Positive Flow (Φ+)	Negative Flow (Φ-)	Net Preference Flow (Φ)	Operating Rule	Positive Flow (Φ+)	Negative Flow (Φ-)	Net Preference Flow (Φ)
Rank 1	**OPR 7**	0.36	0.03	0.33	**OPR 7**	0.39	0.03	0.37
Rank 2	**OPR 15**	0.33	0.03	0.30	**OPR 15**	0.36	0.03	0.32
Rank 3	OPR 11	0.30	0.03	0.27	OPR 11	0.33	0.04	0.29
Rank 4	OPR 3	0.29	0.04	0.25	OPR 5	0.33	0.07	0.26
Rank 5	OPR 5	0.31	0.06	0.25	OPR 3	0.31	0.05	0.26
Rank 6	OPR 13	0.28	0.06	0.22	OPR 13	0.30	0.06	0.24
Rank 7	OPR 9	0.27	0.07	0.21	OPR 9	0.29	0.08	0.21
Rank 8	OPR 1	0.27	0.09	0.18	OPR 1	0.28	0.10	0.18
Rank 9	OPR 16	0.10	0.27	-0.18	OPR 16	0.11	0.29	-0.18
Rank 10	OPR 14	0.09	0.28	-0.18	OPR 14	0.10	0.30	-0.19
Rank 11	OPR 8	0.06	0.30	-0.24	OPR 8	0.07	0.32	-0.25
Rank 12	OPR 6	0.05	0.31	-0.26	OPR 6	0.06	0.33	-0.27
Rank 13	OPR 12	0.06	0.32	-0.26	OPR 12	0.07	0.35	-0.29
Rank 14	OPR 10	0.05	0.33	-0.27	OPR 10	0.06	0.36	-0.30
Rank 15	OPR 4	0.04	0.34	-0.30	OPR 4	0.04	0.36	-0.32
Rank 16	OPR 2	0.04	0.34	-0.31	OPR 2	0.04	0.37	-0.33

The results presented in Table 5.5 suggest that, for both Group 1 (RM1, RM5, RM3, 2WUs and EN) and Group 2 (RM1, RM5, RM3, RM6, WU and EN), there is no difference between PROMETHEE II rankings of top three ranked operating rules, OPR7, OPR15 and OPR11. Furthermore, PROMETHEE 1 rankings given in Figures 5.9 and 5.15 for Group 1 and Group 2 confirm that, the top 2 rank positions could clearly be assigned to OPR7 and OPR15 respectively without any incomparabilities. Therefore, the OPR7 could be considered as the most preferred alternative for both group compositions considered in the case study.

Compared to the current operating rule considered in this study (OPR1), the derived optimum operating rule (OPR7) suggests an increased pumping of water from Yarra River and a reduction of the hydropower generation at Thomson Dam. Furthermore, in addition to the variations made effective in OPR7, the OPR15 includes a tightened demand restriction policy. It can also be concluded that the top two rank positions are very stable for the variation with respect to group compositions considered between Group 1 and Group 2. A general robustness assessment of these results based on a wider variation in the group composition and scenario-weight stability intervals will be presented in Section 5.4.4.

5.4.4 Weight Sensitivity Analysis

The sensitivity of the optimum operating rule (OPR7) derived in Section 5.4.3 in relation to the weights given to different actors (stakeholders) for Group 1 and Group 2 are given in Table 5.6 and 5.7 respectively. The last column indicates the percentage variation of the individual actors' weights that could be reached prior to invalidating the decision, that OPR7 is the optimum alternative among all sixteen operating rules considered. The larger the observed variations, the less likely that the another operating rule would emerge as the optimum, hence more suitable to consider OPR7 as the best alternative. . It should be noted that the sensitivity analysis was carried out considering one actor at a time, keeping other actors at their respective weights.

It is noted from Table 5.6, that in Group 1, the OPR7 will be the highest-ranked alternative irrespective of the weights of assigned for RM1, RM3 and EN (all have recorded 100% weight variations). Also, RM5 and WU have recorded 84.40% and 71.44% weight variations respectively, which could be also considered as fairly high. Therefore, the weights of actors in Group 1 have only marginal influence in the final decision, for the OPR7 to be the optimum alternative.

Table 5.6: Weight Sensitivity of Group 1 Actors on OPR7

Actor	Weight	% Weight	Interval		Interval (%)	
			Minimum	Maximum	Minimum	Maximum
RM1	1	16.67%	0	Infinity	0	100%
RM3	1	16.67%	0	Infinity	0	100%
RM5	1	16.67%	0	27.05	0	84.40%
2WUs	2	33.33%	0	10.00	0	71.44%
EN	1	16.67%	0	Infinity	0	100%

Table 5.7: Weight Sensitivity of Group 2 Actors on OPR7

Actor	Weight	% Weight	Interval		Interval (%)	
			Minimum	Maximum	Minimum	Maximum
RM1	1	16.67%	0	Infinity	0	100%
RM3	1	16.67%	0	Infinity	0	100%
RM5	1	16.67%	0	30.86	0	86.06%
RM6	1	16.67%	0	96.68	0	95.08%
WU	1	16.67%	0	10.00	0	66.47%
EN	1	16.67%	0	Infinity	0	100%

Similarly, Table 5.7 results suggest that for Group 2, the OPR7 will be the highest-ranked alternative irrespective of the weights of assigned for RM1, RM3 and EN. Although, RM5 and RM6 have slightly higher variations compared to in Group 1, WU has recorded only a 66.47% weight variation. In this case too, it is reasonable to consider the sensitivity of OPR7, which is the optimum alternative, as marginal.

5.4.5 General Robustness of the Results

General robustness assessment of top 2 rank positions was carried out in two stages:

1. By varying the group compositions, and
2. By computing the weight stability intervals for different actors in various groups

5.4.5.1 Robustness Assessment with Varying Group Compositions

This analysis indicates the effect on possible changes in the group composition of ranking positions of the alternatives. In order to assess the general robustness of the rankings, six different variations each for Group 1 and Group 2 were considered in the analysis. These variations to the group compositions were obtained by gradually introducing additional RMs into the DMG. As discussed in Section 5.4.1, the RMs were introduced in the order of the magnitude of their contribution to the collective 'All RMs' situation (i.e. RM1, RM5, RM3, RM6, RM4 and RM2). In Group 1 and its variants, WUs were given twice the voice of any other actor in the group whereas in Group 2 and its variants, an equal voice was given to all the actors. The PROMETHEE II top eight rankings for all the scenarios under Group 1 and Group 2 variations are given in Table 5.8 and Table 5.9 respectively.

Table 5.8 and Table 5.9 indicate that OPR 7 and OPR 15 are consistently placed at the top 2 rank positions for all the various group situations considered. Therefore, it can be concluded that, for the entire range of the group compositions considered above, the results reinforce a 'very good' robustness associated with the rankings achieved by the OPR7 and OPR15 as the first-ranked and the second-ranked alternatives. A further robustness assessment based on the scenario-weight stability intervals for actors is discussed in Section 5.4.5.2.

5.4.5.2 Robustness Assessment with Scenario-Weight Stability Intervals

As explained in Section 5.3, at a defined stability level (e.g. top 2 ranks, top 3 ranks etc.), the multi-scenario analysis output of *Decision Lab 2000* gives the stability intervals with respect to the weights of the different actors (or scenarios) in a collective decision. This stability interval indicates, within which bounds the weight of that actor can be modified without affecting the PROMETHEE II ranking, provided that the relative weights of the other actors are not modified (Visual Decision 2003). The weight stability intervals of the individual actors in 'Group 1 & its variants' and 'Group 2 & its variants' are shown in Tables 5.8 and 5.9 respectively, considering a stability level of top 2 rank positions.

Table 5.8: Rankings and Preference Flows of Operating Rules for Group 1 and Its Variants

Group 1 & Its Variants		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
RM1, 2WU, EN	Operating Rule	**7**	**15**	**5**	**11**	**13**	**3**	**9**	**1**
	Net Preference Flow, Φ	0.28	0.25	0.19	0.19	0.17	0.17	0.13	0.11
RMs1 & 5, 2WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.32	0.28	0.25	0.22	0.21	0.19	0.18	0.15
RMs 1,5 & 3, 2WU, EN **Group 1**	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.33	0.30	0.27	0.25	0.25	0.25	0.21	0.18
RMs 1,5,3 & 6, 2WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.35	0.32	0.28	0.25	0.24	0.23	0.20	0.17
RMs 1,5,3,6 & 4, 2WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.35	0.33	0.28	0.24	0.23	0.23	0.19	0.16
RMs 1,5,3,6,4 & 2, 2WU,	Operating Rule	**7**	**15**	**11**	**3**	**13**	**5**	**9**	**1**
	Net Preference Flow, Φ	0.31	0.28	0.25	0.21	0.20	0.20	0.17	0.14

Table 5.9: Rankings and Preference Flows of Operating Rules for Group 2 and Its Variants

Group 2 & Its Variants		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
RM1, WU, EN	Operating Rule	**7**	**15**	**5**	**11**	**3**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.29	0.24	0.21	0.18	0.17	0.17	0.13	0.12
RMs 1 & 5, WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.33	0.28	0.26	0.24	0.23	0.20	0.19	0.17
RMs 1,5 & 3, WU, EN	Operating Rule	**7**	**15**	**11**	**5**	**3**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.35	0.30	0.28	0.27	0.26	0.23	0.22	0.20
RMs 1,5,3 & 6, WU, EN **Group 2**	Operating Rule	**7**	**15**	**11**	**5**	**3**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.37	0.32	0.29	0.25	0.26	0.26	0.24	0.21
RMs 1,5,3,6 & 4, WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**13**	**5**	**9**	**1**
	Net Preference Flow, Φ	0.30	0.27	0.25	0.21	0.20	0.19	0.17	0.13
RMs 1,5,3,6,4 & 2, WU, EN	Operating Rule	**7**	**15**	**11**	**3**	**5**	**13**	**9**	**1**
	Net Preference Flow, Φ	0.32	0.28	0.25	0.22	0.21	0.21	0.18	0.14

Across a group and its variations, the maximum value of the minimum weights and the minimum value of the maximum weights (marked bold red in Tables 5.10 & 5.11) give the stable weight range for each actor, so that the top two respective ranks remain with OPR7 and OPR15. For example, across the Group 1 & its variants, RM1 has $\text{Min}_{(\text{max})}$ = 10% and $\text{Max}_{(\text{min})}$ = 59%. Therefore, RM1's weight could vary between 10% and 59% (i.e. 49% variation) but still maintaining the group decision valid with respect to the top two rank positions. The bandwidths of weight ranges thus derived are presented in Table 5.12. For all the group situations considered above, the bandwidth of each actor is an indication of their ability to make a group decision valid or invalid. Smaller the bandwidth, the more sensitive their preferences would be to overturn the group decision. A greater average bandwidth over all the actors would indicate a more robust top two ranked solutions.

Table 5.10: Weight Stability Intervals of the Actors - Group 1 & Its Variations (Stability level = top 2 ranks)

Actor	RM1, 2WU, EN						RMs1&5, 2WU, EN						RMs 1,5&3, 2WU, EN **Group 1**					
	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%
RM1	1	0.35	5.90	**25%**	**10%**	66%	1	0.00	8.27	**20%**	0%	67%	1	0.00	7.30	**17%**	0%	**59%**
RM2																		
RM3													1	0.00	7.51	**17%**	**0%**	**60%**
RM4																		
RM5							1	0.00	2.91	**20%**	0%	42%	1	0.00	3.02	**17%**	0%	38%
RM6																		
2WU	2	0.34	5.71	**50%**	**14%**	74%	2	0.00	8.17	**40%**	0%	73%	2	0.00	10.00	**33%**	0%	71%
EN	1	0.00	Infinity	**25%**	**0%**	**100%**	1	0.00	Infinity	**20%**	0%	100%	1	0.00	Infinity	**17%**	0%	100%

Actor	RMs 1,5,3&6, 2WU, EN						RMs 1,5,3,6&4, 2WU, EN						RMs 1,5,3,6,4&2, 2WU, EN					
	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%
RM1	1	0.00	11.64	**14%**	0%	66%	1	0.00	16.76	**13%**	0%	71%	1	0.00	15.55	**11%**	0%	66%
RM2													1	0.00	3.80	**11%**	**0%**	**32%**
RM3	1	0.00	12.00	**14%**	0%	67%	1	0.00	17.28	**13%**	0%	71%	1	0.00	16.03	**11%**	0%	67%
RM4							1	0.00	7.99	**13%**	**0%**	**53%**	1	0.00	10.87	**11%**	0%	58%
RM5	1	0.00	4.20	**14%**	0%	41%	1	0.00	5.54	**13%**	0%	44%	1	0.00	4.34	**11%**	**0%**	**35%**
RM6	1	0.00	85.94	**14%**	0%	93%	1	0.00	75.31	**13%**	**0%**	**92%**	1	0.00	105.93	**11%**	0%	93%
2WU	2	0.00	9.91	**29%**	0%	66%	2	0.00	8.92	**25%**	0%	**60%**	2	0.00	11.77	**22%**	0%	63%
EN	1	0.00	Infinity	**14%**	0%	100%	1	0.00	Infinity	**13%**	0%	100%	1	0.00	Infinity	**11%**	0%	100%

Table 5.11: Weight Stability Intervals of the Actors - Group 2 & Its Variations (Stability level = top 2 ranks)

Actor	RM1, WU, EN						RMs1&5, WU, EN						RMs 1,5&3, WU, EN **Group 2**					
	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%
RM1	1	0.18	2.95	**33%**	8%	60%	1	0.16	5.32	**25%**	5%	64%	1	0.07	4.35	**20%**	2%	52%
RM2																		
RM3													1	0.00	4.47	**20%**	0%	53%
RM4																		
RM5							1	0.00	2.12	**25%**	0%	41%	1	0.00	2.23	**20%**	0%	36%
RM6																		
WU	1	0.34	5.71	**33%**	14%	74%	1	0.00	8.17	**25%**	0%	73%	1	0.00	10.00	**20%**	0%	71%
EN	1	0.00	Infinity	**33%**	0%	100%	1	0.00	Infinity	**25%**	0%	100%	1	0.00	Infinity	**20%**	0%	100%

Actor	RMs 1,5,3&6, WU, EN						RMs 1,5,3,6&4, WU, EN						RMs 1,5,3,6,4&2, WU, EN					
	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%	wt	Min	Max	%wt	Min%	Max%
RM1	1	0.00	8.69	**17%**	0%	63%	1	0.00	13.81	**14%**	0%	70%	1	0.00	12.60	**13%**	0%	64%
RM2													1	0.00	3.13	**13%**	0%	31%
RM3	1	0.00	8.95	**17%**	0%	64%	1	0.00	14.23	**14%**	0%	70%	1	0.00	12.99	**13%**	0%	65%
RM4							1	0.00	9.00	**14%**	0%	60%	1	0.00	11.88	**13%**	0%	63%
RM5	1	0.00	3.40	**17%**	0%	41%	1	0.00	4.74	**14%**	0%	44%	1	0.00	3.55	**13%**	0%	34%
RM6	1	0.00	96.68	**17%**	0%	95%	1	0.00	86.04	**14%**	0%	93%	1	0.00	116.67	**13%**	0%	94%
WU	1	0.00	9.91	**17%**	0%	66%	1	0.00	8.92	**14%**	0%	60%	1	0.00	11.77	**13%**	0%	63%
EN	1	0.00	Infinity	**17%**	0%	100%	1	0.00	Infinity	**14%**	0%	100%	1	0.00	Infinity	**13%**	0%	100%

Table 5.12: Weight Ranges of Actors for Stability of Top Two Rank Positions

Group 1 & Its Variants				Group 2 & Its Variants			
Actor	Min (max) (%)	Max (min) (%)	Bandwidth (%)	Actor	Min (max) (%)	Max (min) (%)	Bandwidth (%)
RM1	10	59	49	RM1	8	52	44
RM2	0	32	32	RM2	0	31	31
RM3	0	60	60	RM3	0	53	53
RM4	0	53	53	RM4	0	60	60
RM5	0	35	35	RM5	0	34	34
RM6	0	92	92	RM6	0	93	93
2WU	14	60	46	WU	14	60	46
EN	0	100	100	EN	0	100	100
Average band width (%)			**58.4**	Average band width (%)			**57.6**

The average bandwidth figures given in Table 5.12, i.e. 58.4% and 57.6% suggest that the OPR7 and OPR15 will respectively maintain their best and second best rank positions for an approximate average weight variation of 58%, which is also valid for all the variations in group compositions considered in the above analysis.

5.5 Summary

Sensitivity and robustness measures that have been reported in the literature, to study the effect of the variations in different uncertain parameters on the conclusions drawn from Multi-Criteria Decision Aiding (MCDA) were discussed in early part of the chapter, with particular reference to some water resources planning and management applications. Many authors have recognised the importance of critically reviewing the input data in MCDA and examine the sensitivity of results to the different plausible sets of input data, since in MCDA process, the data input is constantly scrutinised as the Decision Maker (DM) wishes to understand the implications and possible inconsistencies of his/her judgements. There are two types of input data in discrete MCDA; objective data related to Performance Measure (PM) evaluations and subjective data related to DMs' preferential judgements. Uncertainties in these input data may arise either due to:

- Technical errors in evaluation procedures where human judgements are often leading to uncertainty, and/or
- Inability of quantifying and depicting the data by a single representative value.

To deal with the first type of uncertainty, it had been a common practice in MCDA to examine the sensitivity of output for possible variations in PM weights or PM evaluations. The second type of uncertainty had been addressed in the past by introducing stochastic extensions to the available MCDA methods. However, any attempts to study the sensitivity due to preference threshold values in outranking methods were rarely sighted in literature. The case study example was analysed mainly for the uncertainty due to human judgements related to group decision-making. It included the variations in group compositions and the weights (voices) attached to the different actors in a Decision Making Group (DMG).

The typical decision analysis features in *Decision Lab 2000* software were also explained focussing on its capabilities to:

- Provide an insight into the decision problem,
- Derive the PROMETHEE I and PROMETHEE II rankings of alternatives,

- Establish the sensitivity of the results to some parameter uncertainty,
- Assess the robustness of the results, and
- Deal with group decision-making situation through multi-scenario analysis.

PROMETHEE I partial rankings, PROMETHEE II complete rankings and the GAIA-Scenario plane were used to determine the optimum (or most preferred) operating rule among the 16 alternative operating rules for the case study. The decision analysis process involved various decision-making situations including eight single DM cases and three group decision-making cases. The final PROMETHEE ranking was obtained for two group DMG cases (six actors each) with different stakeholder representations. OPR7, the operating rule suggesting an increased pumping of water from Yarra River and a reduction of the hydropower generation at Thomson Dam emerged to be the most preferred alternative operating rule for both the DMGs considered in the study.

The weight sensitivity of actors in both the DMGs revealed that the OPR7 is the optimum alternative for a wide variation of group compositions. The general robustness assessment identified the top two ranked alternatives, i.e. OPR7 and OPR15 were very robust within the plausible limits of the group variations and weights of different actors in a DMG.

References…………

Chapter 6: Conclusions and Recommendations

6.1 Introduction

In concluding the thesis, this final chapter lays down a brief summary of the work undertaken to fulfil the aims of the research study, the conclusions drawn from the analyses carried out in the previous chapters, recommendations derived from the conclusions, limitations of the study and areas for further research.

This study attempted to strengthen the decision analysis module of a generic decision support framework previously proposed by Perera et al. (1999), and detailed in Section 2.6, which was aimed at deriving optimum operating rules for urban water supply systems. The current study proposed a multi-objective decision analysis framework, which utilises two software packages, REALM (REsource ALlocation Model) (Perera and James 2003) and *Decision Lab 2000* (Visual Decision 2003). In the basic setting proposed, the decision analysis process originates with a set of pre-selected feasible alternative operating rules and a family of system performance measures (PMs).

An approach towards the incorporation of stakeholder preferences on various objectives related to water use has been a central feature in this framework, which facilitates exploration and learning to a great extent. The framework will gradually advance through interactivity, arriving at a ranking of the alternative operating rules. The ranking is based on compromising solutions according to the system performance under the alternatives considered and preferences on PMs of the Decision Makers (DMs) or stakeholders. In using this framework, it should be stressed however, that the aggregation and final ranking of the alternatives should not be the main concern. The framework is more advantageous and effective in facilitating an insight into the problem and demonstrating the sensitivity and robustness of the results, while partially leaving the final choice to the DM. Among the capabilities of the proposed framework is the effective handling of:

- Various operational objectives in decision process
- Uncertain streamflow and demand conditions
- Large number of alternative operating rules

- Stakeholder preferences on different objectives
- Varying voices of the stakeholders in group decision making

The Melbourne water supply system case study analysed in this study, covered four operational objectives, a single streamflow and demand condition, sixteen alternative operating rules, preferences of three stakeholder groups and two group decision-making situations. The proposed framework was used on the case study example to provide a clear insight into the decision problem with visual displays of the behaviour of the alternatives considered, while facilitating sensitivity and robustness analyses on the derived results.

6.2 Conclusions and Recommendations of the Study

The major conclusions and the recommendations of the study are presented below in five different sections related to various aspects of the study.

6.2.1 Multi-Criteria Decision Analysis

The multi-criteria decision aiding (MCDA) techniques, which evolved through the last three decades are gradually gaining recognition from the strategic DMs, demonstrating stronger theoretical foundation in the procedures and their diversity through a vast range applications.

Optimisation of an objective function having real quantitative values is often defended against multi-criteria choice due to its strong theoretical base. However, as opposed to the single objective optimisation techniques, the MCDA techniques effectively handle the complex and multidimensional problems with constructive participation of the DMs, considering several facets of a decision problem. The MCDA techniques make an important contribution to the practical decision making process by providing:

- Realism – the best compromising solution in terms of multiple objectives and multiple DMs’ (or stakeholders’) preferences
- Transparency – a structured framework for subjective decisions

- Subjectivity – the recognition for DMs’ experience
- Learning through exploration – the sensitivity and robustness analyses, and
- Flexibility – the freedom of judgement to the DMs

Therefore, in facing the reality and trying to understand what is subjective, what is personal and what can be shared in a complex decision situation, multi-criteria decision aiding is undoubtedly superior to single objective optimisation.

The available MCDA techniques discussed in this thesis differ with each other in the quality and quantity of input information requested, the methodology used, their user-friendliness, the sensitivity tools offered, the mathematical properties they verify, and the availability of software tools. None of these methods can be considered as the ‘super method’ appropriate to all decision-making situations. The choice of a suitable MCDA method in a practical sense should carefully consider the issues such as:

- Type of the problem in hand,
- User acceptance of the method judged through simplicity and interactivity of the method,
- Nature and the quantity of input information (what is required and what can be accomplished), and
- Expectations of the DMs in terms of accuracy, time and effort required.

The discrete MCDA applies where the decision problem is defined by a finite number of alternatives and a family of PMs (arising from different perspectives) on which the alternatives are evaluated. The problem could also have a third dimension if it involves multiple DMs and/or uncertainties in the evaluations. In general, the uncertainties in the evaluations could mainly occur due to varying streamflow/demand patterns or different PM values suggested by different DMs. The MCDA outranking methods belonging to this discrete type, are uniquely characterised by the limited degree to which the disadvantages on a particular viewpoint may be compensated by the advantages of other viewpoints. The MCDA techniques will quite clearly display the optimum choice unless the alternatives are very close to each other in terms of their performance. However, with a closely matched set of alternatives, the final decision may have a certain arbitrariness attached to it.

There are a growing number of MCDA software packages in aid of implementing the discrete MCDA methods. In the context of water resources management, these MCDA software tools built with decision support systems could continue to provide the necessary support for managers to systematically incorporate the stakeholder preferences in the decisions and to arrive at rational operational decisions through exploration and learning.

The proposed framework for determining optimum operating rules for urban water supply systems in this study incorporates the *Decision Lab 2000* software, which utilises the PROMETHEE/GAIA outranking method (a preference aggregation method) as its decision analysis module. This decision module is recommended as a promising tool either as a stand-alone or built-in facility in a decision support framework that yields reliable results for problems where simplicity, transparency and interactivity are of prime importance.

6.2.2 Stakeholder Participation in Water Supply System Operations

There is a growing shift towards the methodical inclusion of stakeholder preferences in practical decision making situations related to sustainable water resources management. The community consensus is also seen as a measure of sustainability while natural resources systems are reported to be rapidly depleting with fast development. In Melbourne area, though there were many instances where community consultations had played a major role in formulating strategies for water resources management, a structured framework is yet to be identified where stakeholders can be directly involved in the decision process.

The proposed decision support framework in this study combines a trusted headwork planning model, with a freshly introduced interactive decision module that facilitates the active participation of the stakeholders to understand the problem on hand, and arrive at a compromising solution. A suitable Decision Making Group (DMG) could be formed with adequate representations from the affected stakeholder categories. Once the individual actors of the DMG are acquainted with the problem itself, the constructive participation of all DMG actors in the decision process enhance their thinking to interactively broaden the decision perspectives, enriching the analysis.

The stakeholder preference parameter evaluations are considered to be more (or less) subjective in nature and tend to vary for reasons stretching beyond the characteristics of the decision problem. Also, in the context of multi-criteria decision aiding, determining the stakeholder preference parameters is considered to be a difficult and a tedious process.

6.2.3 Stakeholder Preference Elicitation and Modelling

A detailed methodology to elicit stakeholder preference parameters as required by PROMETHEE and Decision Lab 2000 was proposed and used in this study. Representatives from three major stakeholder groups of the Melbourne water supply system (i.e. resource managers, water users and those representing environmental interests) participated in an interviewer assisted questionnaire survey to express their preferences on eight system performance measures.

Though eliciting preference intensities from the resource managers was seemed to be straightforward using the generalized preference function types proposed in the PROMETHEE method, an attempt was made to identify and develop an indirect approach for other stakeholder groups who were not familiar with either the feasible ranges of the PM values or the generalized preference function types described in the PROMETHEE method. However, the “Revised Simos’ Procedure”, the technique used to collect information on weights, proved to be well accepted by all respondents.

The stakeholder preferences often have a great influence on the final decision, at the same time, bringing in some uncertainty into the decisions. Therefore, preference elicitation and modelling is an area, which should be handled carefully, to reflect the stakeholders’ views as accurately as possible. During the process of MCDA, the sensitivity and robustness analyses also give an insight into the problem by providing the DMs with an understanding of the system behaviour under the varying nature of these volatile preference parameters.

6.2.4 Optimum Operating Rules for Urban Water Supply Systems

In view of fulfilling various stakeholder priority objectives related to water supply system operations, the resources managers could often visualise the existence of quite a number of alternative ways of operating the system (or operating rules). These alternative operating rules usually satisfy the priority objectives of the stakeholders to different extents. Therefore, it is difficult to make a rational judgement based on their intuition as to the:

- Best-suited priority order of the stakeholder objectives, or
- Closest-matching operating rule in meeting those objectives.

The evaluation of alternative operating rules in terms of the system performance often facilitates this judgement. However, the complexity of the evaluation process increases significantly with the number of alternatives and the number of system performance measures (PMs) that had been involved in prescribing the system performance.

In the Melbourne water supply system case study, the system specific operational details such as the 3 major stakeholder groups, the overall goal, the 4 main objectives, the 8 PMs and the 16 alternative operating rules were identified through the discussions with MW officials. The alternative operating rules were generated from possible variations appeared to bring about an improvement to the current system operations. This study focused on the following four areas of system operations:

- Demand restriction policy,
- Pumping/treatment at Sugarloaf reservoir,
- Hydropower generation at Thomson and Cardinia reservoirs, and
- Minimum passing flows in Yarra river and Thomson river.

The typical decision analysis features in *Decision Lab 2000* software were explained in relation to the alternative operating rules and the PMs selected for the case study, focussing on its capabilities to:

- Provide an insight into the decision problem,

- Derive the PROMETHEE I and PROMETHEE II rankings of alternatives,
- Deal with group decision-making situation through multi-scenario analysis,
- Establish the sensitivity of the results to uncertainty in the preference parameters, and
- Assess the robustness of the results due to varying DMG compositions.

PROMETHEE I partial ranking, PROMETHEE II complete ranking and the GAIA-Scenario plane were utilised to determine an optimum (or most preferred) operating rule among the 16 pre-selected alternative operating rules. For this, the PM evaluations of alternative operating rules were combined with the stakeholder preferences to arrive at a compromising solution. The results were first examined under all possible single DM situations and with a DMG with all RMs. The final PROMETHEE ranking was obtained for two DMGs (with six actors each), giving different stakeholder representations.

Compared with the current operating practice, the operating rule (OPR7) suggesting an increased pumping of water from Yarra River and a reduction of the hydropower generation at Thomson Dam emerged to be the optimum operating rule for both the DMGs considered in the study.

6.2.5 Sensitivity Analysis and Robustness Measures

The excellence of a decision support framework will depend not only on the goodness of the calculation procedures involved, the theoretical foundations and numerical precision, but also on the quality of the input data. With the aid of decision support frameworks, the DMs should be able to interactively construct, explain and ‘sell’ a decision. For this, the frameworks should maintain the minimum requirements of reliability (assessed through sensitivity) and robustness enabling discussion and explanation.

There are two types of input data in discrete MCDA; the objective data related to PM evaluations, and the subjective data related to DMs’ preferential judgements. The built-in uncertainty analyses are often attached to the integrated MCDA software tools of the decision support frameworks, and they mostly address the sensitivity and robustness issues related to DM's preference parameters on the PMs.

There are numerous sensitivity and robustness measures that have been proposed by various researchers to study the effect of the variations in different uncertain parameters on the conclusions drawn from MCDA analyses. A sensitivity and robustness analysis tool is an essential component in MCDA framework, to provide the necessary confidence for DMs in making decisions with reasonable certainty. It is important to criticise the input data and examine the sensitivity of the results to the different plausible sets of data, since in MCDA process, the data input is constantly scrutinised as the DM wishes to understand the implications and the possible inconsistencies of his/her judgements.

The uncertainty of input data in MCDA, as discussed in literature, mainly appears for two reasons: technical aspects in the evaluation procedures and inability to represent the PM evaluation by a single value. To deal with the first type, it is a common practice in discrete MCDA to examine the sensitivity of output results for possible variations in PM weights or PM evaluations. However, any attempts to study the sensitivity due to preference threshold values in outranking methods are rare in literature. The second type of uncertainty is usually addressed by introducing stochastic extensions to the available MCDA methods.

Most of the discrete MCDA software tools attempt to address to the question of "Does the order (ranking) change if the parameters (weights/preference thresholds etc.) are changed by a given amount?" by providing new results for each of the new set of input data. *Decision Lab 2000* software provides a comprehensive sensitivity analysis for PM weights for a single DM case. However, for Group Decision-Making (GDM) setting, it does not facilitate either the sensitivity or robustness analysis of PM weights given by the individual actors in the DMG; instead the sensitivity analysis is facilitated through the weights assigned to individual actors in the group. In either case, it does not assist in examining the sensitivities due to preference threshold values. However, in absence of the built-in sensitivity facilities for GDM situations, the trial and error methods can be used.

The detailed uncertainty analyses carried out for the case study mainly focussed on some specific areas of MCDA module of the proposed decision support framework with respect to group decision-making situations as follows:

- Sensitivity of the results due to variations in the weights assigned to the various actors in DMG
- General robustness of the results due to varying group compositions in DMG

The case study results are derived and analysed for two GDM situations. For both DMGs in the case study example, the in-built features of *Decision Lab 2000* software were utilized to examine the sensitivity of final PROMETHEE rankings, for the weights assigned to individual actors.

The weight sensitivity of actors, on the decision that the optimum operating rule (OPR7) to be the best alternative is proved to be marginal. Also the general robustness assessment confirmed that the OPR7 is very robust within the plausible limits of the group variations and possible variations to the weights of different actors in a DMG.

6.3 Limitations of the Study and Recommendations for Further Research

A simulation model and a discrete MCDA module were integrated into the decision support framework proposed in this study. The framework can be effectively applied for analysing operational decisions related to multi-purpose, multi-reservoir water supply systems, subject to certain limitations which are mostly inherited from the specific methodologies adopted. The details of important features of the framework were covered with illustrations on the case study example. However, due to the limitations of time and effort allocated for this study, there were certain other areas with potential improvements, which could not be explored. Those areas are identified in this section and recommended for further research.

The sensitivity analysis with ‘what-if’ notions in discrete MCDA could be divided into two main levels (Pomerol and Barba-Romero 2000): those concerning the input data (first level) and those concerning the MCDA models (second level). After a detailed survey on the available MCDA methods and software, PROMETHHEE/*Decision Lab 2000* was chosen for the current study mainly due to its simplicity and transparency. Hence, this study only covered the first level of sensitivity analysis concerning the possible variations in voices of the stakeholders in GDM situations using in-built sensitivity analysis and robustness measures of the decision module. It is important to study the effect on the final decision, i.e. optimum operating rule, on the choice of the MCDA method. Therefore, this aspect of sensitivity analysis concerning the MCDA models is recommended for a further study.

It is necessary to decide on a feasible set of alternative operating rules prior to the analysis when using this framework. There could be an instance where the optimum operating rule was not included in the pre-selected set of alternatives due to human error. However, to avoid such situations, a separate module for generating feasible alternatives combining all aspects of the operation policies would be useful. A further study could improve the proposed framework by suggesting a suitable module for generating alternative operating rules.

While maintaining the three properties: exhaustiveness, consistency and non-redundancy within the family of PMs, it is advised that the number of PMs should not exceed about 20 and ideally be kept around 7-10 for clear visual representation of the results. With large number of PMs, difficulty may also be found to occur during eliciting weights of PMs that need to be judged by each DM separately in a DMG.

When simulation and decision support modules are integrated into automated generic decision support frameworks, it is very important to ensure the above properties of PMs at an early stage, since it will be difficult to add any PMs once the framework is fully developed. It is suggested to carefully consider and include all the aspects of the urban water supply system operations at the initial stages of the process. Whenever, any specific problem identifies certain areas are not relevant, while carrying out the analysis, DMs will always have the choice of assigning zero weights to the PMs concerned and eliminating them.

Four operational objectives related to social, economic, environmental and functional aspects of managing the Melbourne water supply system were taken into consideration in the case study, for evaluating alternative operating rules using eight system PMs.

It should be noted that apart from the limitations stemming from the PROMETHEE outranking method, the final results derived for the case study are valid subject to the following limitations:

- Political consideration was not taken into account when selecting objectives, although it was seen as a very influential and a debatable concern for water related issues in Melbourne.
- Two DMGs are considered to be hypothetical, where selective samples of water users and environmentalists provided their preferences for the final decision.
- A single streamflow and demand scenario is used and the stochastic nature of the PM evaluations was not considered.

This study attempted to present an indirect approach for stakeholder preference parameter elicitation and modelling required for PROMETHEE/*Decision Lab 2000*. The 'Revised Simos Procedure', the ordinal method used to collect information on PM weights, was well accepted by all survey respondents.

Modelling the preference thresholds (i.e. '*p*', '*q*', and '*s*') for resource managers was straightforward using the generalized preference function types described in PROMETHEE. However, the other stakeholder groups were not expected to be familiar with either the feasible ranges of the PM values or the generalized preference function types. In this case, the indirect approach suggested in the case study requires considerable time and effort of an analyst who would explain, collect and analyse the preference data for the DMs.

Therefore, in studies where either the time is a limitation or it is difficult to make stakeholders understand the PM definitions, it is worthwhile to examine whether a more simplified approach is appropriate, such as assuming a Type I curve (true criteria; $p = 0$ and $q = 0$) for all the PMs. It should be noted that, when using the Type I curve, the slightest difference in PM evaluations would always be accounted for in the decision without any hesitations of the DM.

For a single DM case, the *Decision Lab 2000* software provides a comprehensive sensitivity and robustness analyses for PM weights. However, for group decision-making setting, it does not facilitate either the sensitivity or the robustness analysis of PM weights given by the individual actors in the DMG; instead the sensitivity analysis is facilitated through the weights assigned to individual actors in the group. Therefore, the sensitivity analysis carried out for the DMGs considered in the case study using the in-built features of the *Decision Lab 2000* covered only the uncertainty involved with the group composition of the DMG (weights given to different actors in the DMG).

In either single DM or GDM case, the *Decision Lab 2000* does not promote the sensitivity or robustness analysis related to preference thresholds. Developing a tool that could carry out sensitivity and robustness related to both types of preference information on PMs, i.e. weights and preference thresholds, in single DM case as well as in DMG case would be useful in understanding the stability of the final ranking of alternatives in terms of these uncertain preference parameters.

In using the proposed framework to derive optimum operating rules for an urban water supply system, a stochastic extension is recommended for decision problems, where either it is not realistic to represent the PM evaluations with a single value or more precision is required by the DMs. In this case, the simulation model will use many streamflow sequences to derive a large number of probable PM evaluations under each of those streamflow sequences. These plausible sets of PM evaluations can then represent the system performance under varied streamflow conditions.

This thesis contained the research work carried out in developing a decision support framework to derive the optimum operating rules for multi-purpose, multi-reservoir urban water supply systems and illustrated it on the Melbourne water supply system case study. The simulation module used in the framework had been in use for a long time in Australia and it is more readily accepted by the DMs. In contrast, the decision module that was more focussed on this study, emerged from the field of MCDA, which is still developing and gaining acceptance among the practitioners. Although MCDA could offer an impressively wide range of possibilities, the modelling of the whole problem (i.e. the alternatives, PMs and preference parameters) is undoubtedly causing a reduction in ambiguity exposing DMs’ preferences and trade-offs, which to a certain extent, may not be favoured by the DMs. Also the MCDA brings in the conflicts to the light, rather that covering them. As Kottemann and Davis (1991) stated:

> “ *The more a method requires direct arbitration between PMs, and hence shows the DM that there is conflict between equally desirable but more or less incompatible ends, the more reluctant is the DM to accept the method.*”

Therefore, from a practical point of view, while the MCDA processes are yet to establish their recognition, the processes themselves should not increase the complexity of the problem, diminishing the greatest benefits of MCDA. What needs to be stressed is that, in improving the quality of decisions, the interactive MCDA frameworks are effective in better responding to the aspirations of all the concerned stakeholders.

References…………

Appendix A: Details of Some Discrete Multi-Criteria Decision Aiding (DMCDA) Software

Table A -1: Limitations and Applications of DMCDA Software Packages

Software	Description	Limitations	Applications	
			General	Water Resources Management
AIM (Version 3.0)	• A progressive information method where the DM gives aspiration levels, and the search is based on an operator that has been defined by a temporary aggregation in which the distance to the aspiration level is minimized. • ELECTRE I is used to search for the alternatives in the neighbourhood of the temporary optimisation • Use of interactive veto levels	• 50 alternatives • 10 PMs • PMs are maximized or minimized or else user can define a goal to be attained		
CRITERIUM DECISION PLUS (CDP 3.0)	• Accepts the uncertainty in weight assessment, and offers immediate graphical feedback from what-if analysis	• 50 alternatives • 7 levels of hierarchy for PMs		
DECISION LAB 2000	• Provides visual information on PM concordance and discordance, and on the relative proximity of alternatives (this can be evaluated too). • A partial outranking relation is shown graphically (PROMETHEE I) or a complete pre-order can be obtained	• 150 alternatives • 150 PMs	• Resource selection: vendors, experts, top managers, etc. • Project ranking:	Protecting waterways from mine action (Mladineo and Knezic

	(PROMETHE II).		funding, contracting, prioritisation, etc. • Strategic planning: acquisition, fusion, expansion, etc. • Performance monitoring: quality insurance, technical standards, etc. • Group decision-making: multiple stakeholder situations (Cil et al. 2005; Genova et al. 2004; Linkov et al. 2006; Martin et al. 1999; Rogers et al. 2004)	2003)
DEFINITE	• A decision support system combining several DMCDA methods • Developed for the Dutch Treasury for public investment planning. • The only known package to use REGIME method		Design of riparian vegetation buffer zones (Qureshi et al. 1999)	
ELECCALC	• The user can globally express preferences about few reference alternatives, and then method can specify initial values for parameters (concordance and discordance coefficients) of ELECTRE II.			

	• From the arbitrary starting values for parameters, the program allows the user to follow interactively the parameters that are compatible with the DM's preferences on the reference set. The parameters are then used for final ranking.			
ELECTRE 1S	• Uses an interactive ELECTRE I methodology enabling the use of pseudo-criteria (criteria with thresholds). • Supports the user in selecting one alternative or a subset of alternatives.		Most of the Applications are reported in French (http://l1.lamsade.dauphine.fr/english/software.html#el2.log)	
ELECTRE III – IV (Version 3.1)	• ELECTRE III starts with a finite set of actions evaluated on a consistent family of pseudo-criteria and aggregates these partial preferences into a fuzzy outranking relation • ELECTRE IV builds several non-fuzzy outranking relations when PMs cannot be weighted • Two complete preorders are then obtained through a 'distillation' procedure, either from the fuzzy outranking relation of ELECTRE III or from the non-fuzzy outranking relations of ELECTRE IV. The intersection of these pre-orders gives most reliable part of the global preference.		Comparison of control options against a chemical pollutant (Siskos et al. 1986); -Ranking of suburban line extension projects (Roy and Hugonnard 1982)	
EXPERT CHOICE	• The software tool of AHP method for computers. There are two main features in AHP, which is used in EXPERT CHOICE. They are as follows: (1) Structuring of the problem as a hierarchical tree diagram – The basic set up has 9 alternatives and 9 PMs. For problems	Forces the user to; • Adapt to a hierarchy structuring with up to five layers of PMs, each node	Design of riparian vegetation buffer zones(Qureshi et al. 1999), Habitat suitability analysis for the Mount Graham squirrel (Pereira and Duckstein 1993)	

	with 5 layers of PMs, the software can handle up to 9^5 criteria and 9 alternatives (this limit can be extended through the ‘Ratings’ function). (2) Use of pair-wise comparisons- (both between criteria to estimate the DM’s desired weights and between alternatives to evaluate each alternative relative to each PM.) • Comparisons are made on a numerical scale (1 to 9) or on a qualitative scale, which can be displayed graphically. ▪ Calculates an evaluation for each alternative by simple weighting, and hence a total pre-order. Useful extra features of the package include: • ‘Ratings’ function to define and evaluate a set of alternatives as if it were a single alternative. Once the best set of alternatives has been chosen, the best alternative within that set can be found. The process can be repeated any number of times. • The package has a diagnostic function for the most likely cause of inconsistency resulting from pair-wise comparisons when the inconsistency co-efficient is greater than 0.1. (AHP will accept certain degree of inconsistency.)	handling up to nine branches • Accepts the theoretical assumptions of simple weighting • Less than nine alternatives (unless entered into ‘Ratings’) and 9^5 PMs.		

HIPRE3+	Uses AHP with considerable extensions. Highly interactive. • Allows modelling in 20 hierarchical levels with 50 elements per level. • Weights are assigned either directly or by pair-wise comparisons, and the user can easily define various utility functions for the criteria. • Runs in DOS environment. Parallel package HIPRE3+ Group Link is a Windows version for group decision analysis. • Web-HIPRE is the internet version of HIPRE3+ for collaborative decision analysis	• 20 hierarchical levels • 50 elements per level		
HIVIEW & EQUITY	• HIGHVIEW and EQUITY assisted decision processes give a balanced view over a wide range of PMs where hard data (eg. financial) is integrated in a rigorous manner with subjective data. • HIVIEW is used for choosing between different management options. • EQUITY is used for resource allocation, budgeting and prioritisation modelling			

LDW	Problem analysis is done in three distinct stages: (1) Structuring a decision (objective part) (2) Assessing preferences ((subjective part) and (3) Reviewing results • In the structuring stage alternatives are first created, followed by the PMs. The worst and best levels are defined for each quantitative PM, and qualitative criteria are given text labels. Evaluation of the alternatives is then carried out. The PMs can be organized in two hierarchical levels, the upper level being called goals (Logical Decisions 1997). • LDW is a good example of how powerful a good representation of objectives and PMs can be in analyzing and modeling a problem (Pomerol and Barba-Romero 2000). • Among the useful features are the possibility of setting satisfaction cut-offs and ability to introduce uncertainty into the evaluations (Pomerol and Barba-Romero 2000).	• Heavily biased towards the weighted sum. • Process of creating alternatives and criteria is rather laborious, lacking a spreadsheet-type matrix that could be filled out directly (Pomerol and Barba-Romero 2000).		
MACBETH	• DM's preferences (utility functions and weights) are extracted by means of qualitative binary comparisons and finally obtained by a linear programming algorithm. Basically MACBETH is intended to help the DM to build consistent cardinal utilities. • Inconsistencies in the DM's estimations may be detected, and suggestions given for solving them		• Tender evaluation (Bana e Costa et al. 2002) • Resource management (Bana e Costa and Oliveira 2002)	

QUALIFLEX	Uses an algorithm based on permutation methods. Compare the various possible rankings of alternatives with the information in the decision matrix. For each ranking, a value index is given, characterizing the matching between the ranking and the values in decision matrix. Ranking with the best index is selected. A distance between each alternative and the best one is also given. • Assessments are highly ordinal; very convenient and robust for the DM • Important feature - able to assign the weights in various different ways such as fixed weights (cardinal value), ranking of criteria (pre-order on the weights) or interval weights (cardinal value interval). • User-friendly and easy navigation between the various options on-screen. • Requires the 'structure' of the model be previously created. Creating models is a tedious job, but various input and output options are available for the model in text, spreadsheet or database format. • Overall performance is effective and features a powerful and attractive graphic interface. • Two advantages - Low information requirement from the DM, and flexibility in defining weights	• Handles up to 500 alternatives and 20 PMs • Inherent with permutation methods is the difficulty of interpreting the results produced • Assumptions associated with weighted sums.		
UTA PLUS	Uses UTA method. Constructs an additive utility function from a preference weak order defined by the user on a subset of reference alternatives. The construction based on a principle of		• Economics (Contant et al. 1987)	• Analyzing groundwater management

	ordinal regression, consists of solving a small LP-problem. • The software proposes marginal utility functions in piecewise linear form as compatible as possible with the given weak order. • Allows the DM to modify interactively the marginal utility functions within limits following from a sensitivity analysis of the ordinal regression problem (friendly graphical interface is available). • Utility function accepted by the DM serves then to define a weak order on the whole set of alternatives.		• Resource allocation (Siskos 1986)	alternatives (Duckstein et al. 1993) • Rural water supply (Roy et al. 1992)
VIMDA	• Uses interactive comparison of alternatives in graphic mode	• Handles up to 500 alternatives and 10 PMs		
VISA	• Friendly graphical interface for adjusting the PM hierarchy and other components (e.g. weights) of the model • Interactive input of weights using bar charts, thermometer scales or numbers		Selection of alternatives for restoration of aquatic ecosystems contaminated by radioactive fallout(Rios Insua et al. 2000)	

Table A-2: Features and Information Sources of DMCDA Software

Software	Software Features				Source
	Operating System	Group Decision making	Sensitivity analysis	Assistance	
AIM	DOS	No	Yes	-	V. Lotfi, School of Management, The University of Michigan, Flint, MI 48502, USA.
CRITERIUM DECISION PLUS (CDP) 3.0	Windows	No	Yes	User's Guide & Help File	http://www.infoharvest.com Free download of CDP 3.0 student version. Complete software is commercially available for American $ 895.
DECISION LAB 2000	Windows	Yes	Yes	User's Guide & Help File	http://www.visualdecision.com Commercially available for Canadian $ 1450 Free download of demo version
DEFINITE	Windows	Yes	Yes	User's Guide & Help File	DEFINITE@ivm.vu.nl R. Janssen, Free University, 1007 MC Amsterdam, Netherlands Janssen (1992) comes with a demo version Commercially available for Euro 1360
ELECCALC	DOS	Yes	Yes	-	L.N. Kiss and J-M Martel, Faculty of Science and Administration, Laval University, Quebec, Canada G1K 7P4 Not commercially available.

ELECTRE 1S	DOS	No	Yes	User's manual is available in French	http://www.lamsade.dauphine,fr/english/software.html#elis Available from LAMSADE Laboratory, University of Paris-Dauphine, France
ELECRTE 111-1V (Version 3.1)	Windows	No	Yes		http://www.lamsade.dauphine,fr/english/software.html#elis Available from LAMSADE Laboratory, University of Paris-Dauphine Free download of Demo version
EXPERT CHOICE (EC 11.5)	Windows	Yes	Yes	User's Guide & Help File	http://www.expertchoice.com Available from Expert Choice Inc., 1501 Lee Highway, Suite 302, Arlington, VA 22209, USA Free download of demo version
HIPRE3+ (Version 3.14)	• HIPRE3+ runs in DOS • HIPRE3+ Group Link is a Windows version • Web-HIPRE is a Java applet which works in any environment	Yes	Yes	User's Guide & Help File	http://www.hut.fi/units/SAL http://www.hipre.hut.fi Free download of demo version
HIVIEW & EQUITY	Windows	Yes	Yes	User's Guide &	www.lse.ac.uk/collections/enterpriseLSE/DecisionSupport.htm

				Help File	Enterprise LSE Limited 8th Floor, Tower One Houghton Street London WC2A 2AE Free download of demo version of both HIGHVIEW3 and EQUITY3 HIGHVIEW3 – UK Pounds 170 (single user) EQUITY3 – UK Pounds 320 (single user)
LDW	Windows	Yes	Yes	User's Guide & Help File	www.logicaldecisions.com Available from Logical Decisions, 1014, Wood Lily Drive, Golden, CO 8041, USA. Free download of demo version
MACBETH	Windows	No	Yes	User's Guide & Help File	http://www.umh.ac.be/~smq Prof. C. Bana e Costa (cbana@alfa.ist.utl.pt) Prof. J-C. Vansnick (Jean-Claude.Vansnick@umh.ac.be) A commercial version may be obtained from Prof. Vansnick.
QUALIFLEX	DOS	No	Yes	User's Guide is not designed as a reference but as a tutorial and no Help File	Software is available on a disk accompanied by the book, 'QUALIFLEX Version 2.3: A Software Package for Multi-criteria Analysis'' by J van der Linden and H. Stijnen.
UTA PLUS	Windows	No	Yes	User's Guide & Help File	http://www.lamsade.dauphine.fr/english/software.html#uta+ Lamsade softwares LAMSADE, Université Paris-Dauphine, Place du Maréchal de Lattre de

					Tassigny, F-75775 PARIS CEDEX 16. Free download of demo version
VIMDA	Windows	No	Yes	User's Guide & Help File	http://www.numplan.fi/vimda/vimdaeng.htm NUMPLAN, Helsinki, Finland numplan@numplan.fi
VISA	Windows	Yes	Yes	User's Guide & Help File	http://www.siml8.com/products/visa.htm Prof. V. Belton, University of Strathclyde, UK. Free download of demo version Single user license retails at $199

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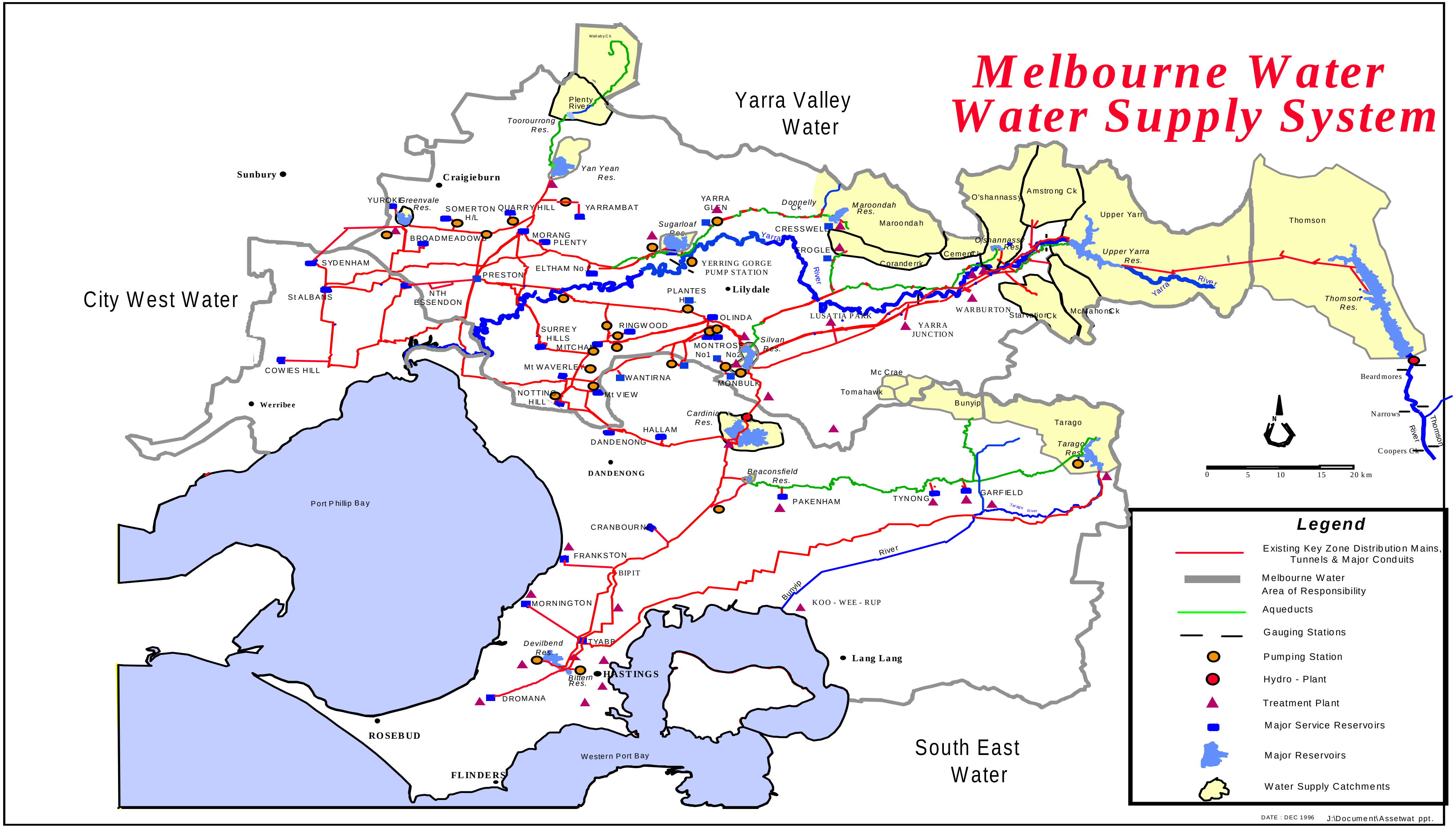
Appendix B: Melbourne Water Supply System



Appendix C: Regulatory Measures in 2002-03 Water Restrictions*

PURPOSE	STAGE OF RESTRICTION	RESTRICTION
Private Gardens	***One***	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Two	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand watering of garden beds 6 -8 am and 8-10 pm, every second day
	Four	• Buckets only may be used to water shrubs and trees
Public Gardens	***One and Two***	• Hand watering and sprinklers any time • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Four	• Buckets only may be used to water shrubs and trees
Swimming Pools	***One and Two***	• Topping up allowed • New pools require prior written authority
	Three	• Topping up allowed using only a hand held hose • New pools require prior written authority
	Four	• Topping up allowed using only a bucket • New pools require prior written authority

Sports Ground	***One***	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Two	• Only the ‘active’ playing areas to be watered and then only by: - Hand watering/sprinklers 6-8 am and 8-10 pm - Automatic sprinklers 1 pm-6 am
	Three	• Only the ‘active’ playing areas to be watered and then only by: - Bucket - Hand held hose if for professional sport
	Four	• Only the ‘active’ playing areas to be watered and then only by bucket or hand held hose if for professional sport. Prior written authority required.
Industry	***One, Two, Three and Four***	• No restrictions
Commercial Garden or Nursery	***One, Two and Three***	• Hand watering/sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Four	• Only by prior written authority
Vehicles	***One***	• Trigger hose only
	Two	• Bucket only
	Three and Four	• Not permitted
Paved Areas	***One, Two, Three and Four***	• Not permitted
Windows	***One, Two and Three***	• Only by using a bucket can filled directly from a tap
	Four	• Not permitted

(Source: www.melbournewater.com.au)

* The above regulatory measures were in effect during 2002-03 when the interview survey was carried out for this study. These measures have been subjected to change many times after 2003, due to severe drought conditions experienced in Melbourne.

Appendix D: Questionnaire - Pilot Survey

Preferences on Water Use – Customer Survey

Pilot testing of the INTERVIEW QUESTIONNAIRE

Instructions to participants:

- Tick the boxes where appropriate.
- If you wish to make additional comments on any of the specific questions or on the questionnaire in general, use the space at the end of page 5.
  Your opinion is very important in identifying the necessary refinements to this questionnaire.
- Please hand over the completed questionnaire in the sealed envelope to Ms. Anna Calabro at the School of Architectural, Civil & Mechanical Engineering.

(Q1) To which of the following age groups do you belong?

18 - 24 ☐
25 – 34 ☐
35 – 49 ☐
50 – 59 ☐
60+ ☐

(Q2) Record the gender

Male ☐
Female ☐

(Q3) Who is your retail Water Company?

City West Water ☐
South East Water ☐
Yarra Valley Water ☐

(Q4) To which customer category do you belong?

Residential ☐
Industrial / Commercial ☐
Any other (please specify) ☐

____

In responding to the following questions, please try to express your views on having a fair (as you think how it should be) balance between the following;

- **a water supply with minimum restrictions**
- **more water saved for the future**
- **more water released to waterways (a healthy eco-system)**
- **an affordable price for water**.

We all know that water is a scarce and a valuable resource. So, it is clear that an improvement of any of these would come with an impact on the others.

For example, accepting the restrictions to a certain extent would mean that we have;
- more water saved for future use,
- more water for animals & plants in and around waterways

and - a reasonable price for water.

For long term planning purposes of the Water Supply System, we have defined an overall goal.

Overall Goal

‘To ensure a safe and reliable water supply at an acceptable cost and in an environmentally sensitive manner for the benefit of the present and future Melbournians.’

(Q5) Do you agree with the above goal?

Totally agree ☐
Partly agree ☐
Do not agree ☐

Water Restrictions (Duration & Reliability of supply)

(Q6) On imposing water restrictions, my desire is to;

Accept it to some extent ………… Go to (**Q7**)

Prefer no restrictions ………… Go to (**Q8**)

Strongly oppose restrictions ………… Go to (**Q10**)

(Q7) The operating rules for the water supply system could be designed to have different ‘**durations**’ of restrictions of varying severity, depending on how much water we want to save for future use. Indicate the time duration (at a stretch) that you think is most reasonable to have water restrictions at each restriction level.
(Please refer to the Attachment 1 to see how the different Stages of restrictions affect different purposes.)

	0 months	3 months	6 months	1 year	2 years	3 years or more
Stage 1						
Stage 2						
Stage 3						
Stage 4						

(Q8) What is the approximate duration (at a stretch), beyond which you do not wish (strongly oppose) to have any kind of (even Stage 1) restriction?

3 months	6 months	1 year	2 years	3 years or more	Other (pl. specify)

(Q9) Reliability of Supply (Maximize)

Reliability of a water supply increases with the total number of months with an unrestricted supply. Indicate your preferences on the % time with an unrestricted supply. (tick preference levels; what you prefer a lot, what is acceptable and what level it shouldn't go beyond)

	Prefer a lot	Acceptable	Strictly not less than
More than 91% (~ >11 months / yr)			
90% - 76% (~ 9 -11 months / yr)			
75% - 51% (~ 6 – 9 months / yr)			
50% - 25% (~ 3 – 6 months / yr)			
Below 25% (~ < 3 months / yr)			

(Q10) Level of Restrictions (Minimize)

Different stages of restriction impose varying levels of severity on watering gardens, vehicle washing etc.(Please refer to the Attachment 1 to see how the different Stages of restrictions affect different purposes.)

In general, how do you feel about these different Stages of restriction?

	Very Lenient	Quite Lenient	Acceptable	Quite Harsh	Extremely Harsh
Stage 1					
Stage 2					
Stage 3					
Stage 4					

For **(Q11)** to **(Q15)**, indicate the levels at which you would personally feel satisfied about the measure indicated in bold letters (tick preference levels; what you prefer a lot, what is acceptable and what level it shouldn't go beyond).

(Q11) Frequency of Restrictions (Minimize)

Water restrictions can occur in the future, as a part of responding to drought conditions. Depending on how much water we want to save for future, the operating rules could be designed to have restrictions at different '**frequencies**'. Indicate your preferences on the following frequencies, assuming Stage 1 restrictions.

	Prefer a lot	Acceptable	Strictly not more than
Every year (100% chance annually)			
Once in 3 years (~33% chance annually)			
Once in 5 years (20% chance annually)			
Once in 10 years(10% chance annually)			
No restrictions (0% chance annually)			

(Q12) River Flows (Maximize)

Currently the minimum environmental flow volumes are released to the waterways to ensure there is enough water for fish, other wildlife and plants. Indicate your preferences on the **amount of water released to our waterways**.

	Prefer a lot	Acceptable	Strictly not less than
High flows			
Moderate flows			
Minimum requirements			
Below minimum requirement			
No water released to waterways			

(Q13) Pumping/Treatment Costs (Minimize)

At times of significant drought periods, sometimes water is pumped from Yarra River to Sugarloaf reservoir as a supplement to the supply. This of course will result in less water flow in the river and accompany some additional costs to all of us.
Indicate your preferences on the **amount of pumping** that should occur.

	Prefer a lot	Acceptable	Strictly not more than
Large amounts			
Moderate amounts			
Small amounts			
Minimal pumping			
No pumping			

(Q14) Hydropower Generation (Maximize)

It is possible to release water from the Thomson reservoir through the hydropower station, depending on the storage level of Thomson. Though this can bring additional revenue to water authorities, the current policy is the ’minimum power generation’ with the water that is surplus to Melbourne’s needs.
Indicate your preferences on the **amount of hydropower generated.**

	Prefer a lot	Acceptable	Strictly not less than
Large amounts			
Moderate amounts			
Small amounts			
Minimal power generation			
No power generation			

(Q15) Minimum Storage of the Reservoirs (Maximize)

Thinking of saving water for future use, indicate your preferred **minimum water levels in our storage reservoirs**. To get an idea, the storage levels (as a % of the total storage) at which we enter different stages of restriction, for each month is given in the Attachment 2 (normally between 45%-55% range we enter Stage 1 restrictions).

	Prefer a lot	Acceptable	Strictly not less than
Over 95% full (> 3 years' supply)			
65% full (~ 2 years' supply)			
50% full (~ 18 months' supply)			
30% full (~ 1years' supply)			
Below 30% full (< 1 years' supply)			

- -

Additional comments, if any: (*Note: this part is included only for pilot testing*)

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Weights Assessment

To assess the performance of the Melbourne water supply system, we have identified 8 key measures as the most crucial ones. They are;

Related to ‘ water restrictions ‘:

(1) Number of months with restrictions (RM)
(2) Worst restriction level (WL)
(3) Duration of restrictions (DR)
(4) Frequency of restrictions (FR)

Related to ‘ costs / revenues ‘:

(5) Pumping /Treatment costs (PC)
(6) Hydropower revenue (HR)

Related to ‘ eco-system ‘:

(7) River flows (RF)

Related to ‘Saving water for future’:

(8) Minimum reservoir storages (MS)

Naturally, each one of the above measures would be of different importance level to you.

Step 1
Each of the nine cards that have been given to you has one measure written on it. A small explanatory note is also given on the back side of each card.
We ask you to place them in a row on a flat surface, in the order of importance that you assign to them, starting with the most important one. (The cards with equally important measures may be grouped together.)

Step 2
Insert in between any white cards given to you, to express the gaps in importance. The greater the difference between the importance, the greater the number of white cards will be.

Record the pattern on the line given below. The first one is the most important measure and the last one is the least important measure.

Most Important ------------↓---------↓---------↓---------↓---------↓---------↓---------↓------------ **Least Important**

No. of Blank cards ☐ ☐ ☐ ☐ ☐ ☐ ☐

(Q17) How many times the most important factor is more important than the least one?

Water Restrictions

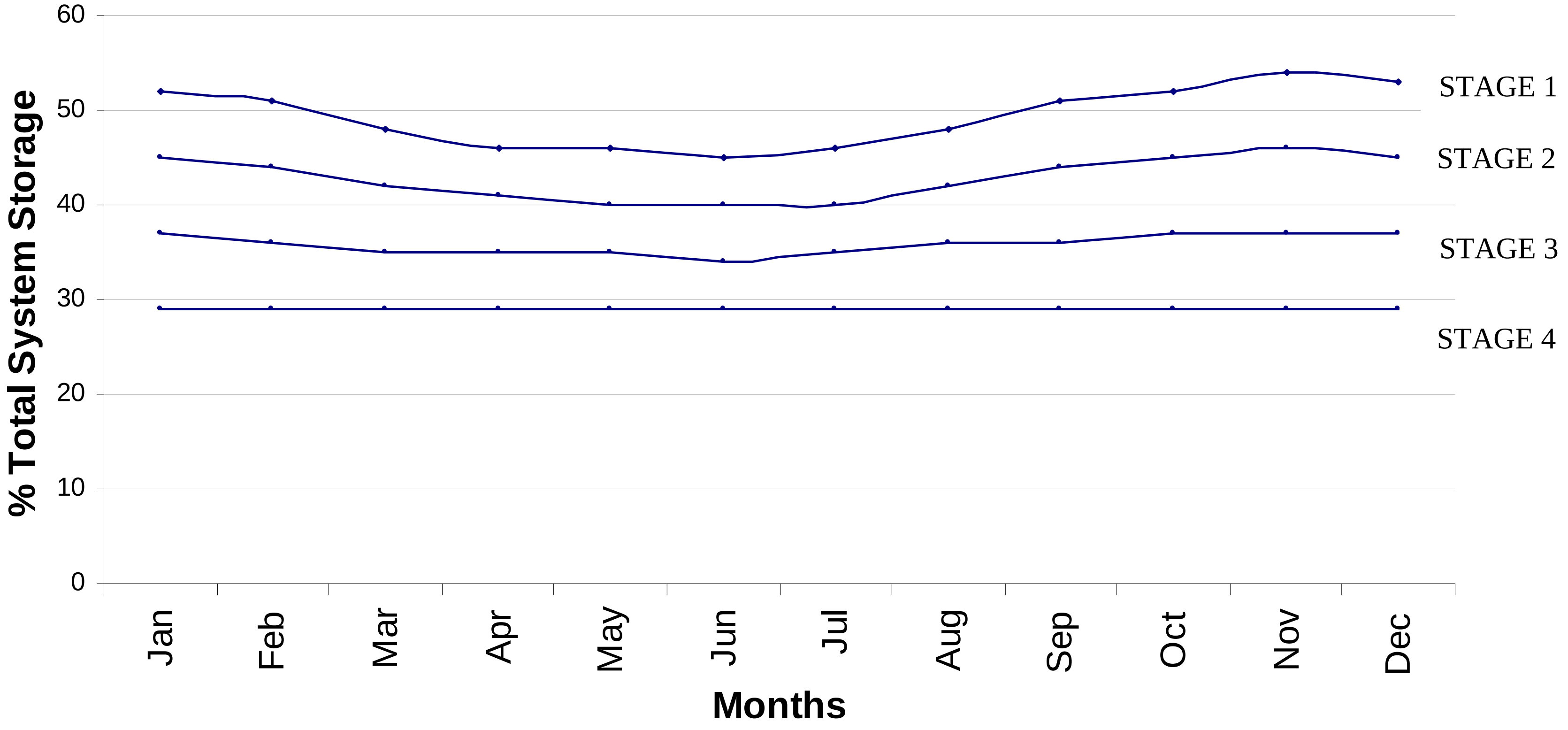
PURPOSE	STAGE OF RESTRICTION	RESTRICTION
Private Gardens	**One**	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Two	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand watering of garden beds 6 -8 am and 8-10 pm, every second day
	Four	• Buckets only may be used to water shrubs and trees
Public Gardens	**One and Two**	• Hand watering and sprinklers any time • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Four	• Buckets only may be used to water shrubs and trees
Swimming Pools	**One and Two**	• Topping up allowed • New pools require prior written authority
	Three	• Topping up allowed using only a hand held hose • New pools require prior written authority
	Four	• Topping up allowed using only a bucket • New pools require prior written authority

Sports Ground	**One**	• Hand watering and sprinklers 6 - 8 am and 8 – 10 pm • Automatic sprinklers 11 pm – 6 am
	Two	• Only the 'active' playing areas to be watered and then only by: - Hand watering and sprinklers 6-8 am AND 8-10 pm - Automatic sprinklers 1 pm-6 am
	Three	• Only the 'active' playing areas to be watered and then only by: - Bucket - Hand held hose if for professional sport
	Four	• Only the 'active' playing areas to be watered and then only by bucket or hand held hose if for professional sport. Prior written authority required.
Industry	**One, Two, Three and Four**	• No restrictions
Commercial Garden or Nursery	**One, Two and Three**	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm – 6 am
	Four	• Only by prior written authority
Vehicles	**One**	• Trigger hose only
	Two	• Bucket only
	Three and Four	• Not permitted
Paved Areas	**One, Two, Three and Four**	• Not permitted
Windows	**One, Two and Three**	• Only by using a bucket can filled directly from a tap
	Four	• Not permitted

Attachment 2

Restriction Entry Trigger Points

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stage 1	52	51	48	46	46	45	46	48	51	52	54	53
Stage 2	45	44	42	41	40	40	40	42	44	45	46	45
Stage 3	37	36	35	35	35	34	35	36	36	37	37	37
Stage 4	29	29	29	29	29	29	29	29	29	29	29	29



Appendix E1: Questionnaire - Survey with Resource Managers

Interview Survey - Preferences on Objectives

Melbourne Water Supply System

(Resource Manager Group)

Information for the participants:

- The information collected during this survey will be treated as confidential.
- In responding to the questions, please try to express your views **as a Resource Manger** on having a fair balance between the following competing objectives;
  - maximise level of service
  - Maintain an affordable water supply
  - improve the environment
  - maximize supply sustainability

Some background information is provided in the Attachment. Please read the attachment before answering the questions.

- The completed questionnaire (in the sealed envelope provided) may be anonymously forwarded to Dr. Udaya Kularathna.

The overall goal for long term planning of the Water Supply System is stated below.

Overall Goal

'To ensure a safe and reliable water supply at an acceptable cost and in an environmentally sensitive manner for the benefit of the present and future Melbournians.'

(Q1) Do you agree with the above goal? (Please tick)

Totally agree ☐
Partly agree ☐
Do not agree ☐

Weights Assessment

This will be done in two stages; one for Performance Measures (PM)s and one for higher level objectives.

(a) Weights Assessment on PMs

The relative importance of PMs is expressed in terms of weights.

Each of the eight cards has the name of a PM written on it. A small explanatory note is also given on the back of each card.

Step 1
Place them in a row representing the **order of importance** that you assign to them, starting with the most important one. (The cards with equally important measures may be grouped together.)

Step 2
In between the above cards, insert any number of white cards that will be given to you, to express the **gaps in importance**. The greater the difference in the importance, the greater the number of white cards will be.

Record the pattern on the line given below. The first one is the most important measure and the last one is the least important measure.

Most Important ↓ ↓ ↓ ↓ ↓ ↓ ↓ **Least Important**

No. of Blank cards ☐ ☐ ☐ ☐ ☐ ☐ ☐

(Q2) How many times the most important PM is more important than the least important one?

(b) Weights Assessment on Higher Level Objectives

Repeat the procedure in (a), *(Step 1* & *Step 2)* for the four cards representing the broad objectives; 'Level of Service', 'Affordability', 'Environment' and 'Supply Sustainability'. Record the pattern.

Most Important ↓ ↓ ↓ **Least Important**

No. of Blank cards ☐ ☐ ☐

(Q3) How many times the most important category is more important than the least important one?

(Q4) Indicate a preference function type for each PM in the following table and provide the values for p / q / s, as appropriate.

Performance Measure (PM)	Definition	Min / Max	Acceptable Range of Variation (Approx.)	Units	Preference Function Type (select from the six types) and provide parameter values p and q or s
Supply Reliability	Percentage of non-failure months to the total number of months in the simulation period.	Maximise	[95 – 100]*	%	
Worst Restriction Level	Worst stage of restriction reached during the simulation period.	Minimise	[0 – 3] *	-	
Duration of Restrictions	Maximum consecutive duration of any form of restrictions reached during the simulation period.	Minimise	[0 – 12] *	Months	
Frequency of Restrictions	Annual chance of occurrence of a restriction during the simulation period.	Minimise	1/5 – 1/25 (0.2 - 0.04)	-	
Pumping / Treatment Cost	Average annual cost of pumping & treatment at Yering Gorge for the simulation period.	Minimise	[2 – 8] **	$ mil. per year	
Hydropower Revenue	Average annual revenue from hydropower generation at Thomson and Cardinia for the simulation period.	Maximise	[2.85 – 5.4] #	$ mil. per year	
River Flows	Average annual total flow downstream of harvesting sites (this includes the flow from catchments below MW reservoirs) for the simulation period.	Maximise	[160 – 240]##	Gl/ year	
Total System Minimum Storage	Minimum monthly total storage volume reached during the simulation period.	Maximise	611 - 700	1000 Ml	

* As per Bulk Water Supply Agreement (BWSA) between MW and retail water companies

** Based on the cost of Winneke water, assuming a rate of $ 60 per Ml.

\# Based on Thomson & Cardinia plants, assuming a rate of $ 20 per Ml

\#\# Considering Yarra River at Yering Gorge & Thomson River downstream of Coopers Creek.

Appendix E2: Additional Information - Survey with Resource Managers

Attachment: Overview of the Research Project and the Interview Survey

Project Title:
Multi-objective Optimal Operation of Urban Water Supply Systems

Aims of the Research:
- Develop a methodology and a Decision Support System (DSS) to investigate the optimum operating rules for urban water supply systems, considering the preferences of various stakeholder groups.

Introduction:
Alternative operating rules will be compared and analysed using a set of system **Performance Measure (PM)** s that summarise the system performance under these rules. Listed below are eight key PMs that fall under 4 categories of objectives.

Objective 1: Maximise 'Level of Service';

(1) Supply Reliability (SR)
(2) Worst Restriction Level (WL)
(3) Duration of Restrictions (DR)
(4) Frequency of Restrictions (FR)

Objective 2: Maintain an 'Affordable Water Supply';

(5) Pumping / Treatment Costs (PC)
(6) Hydropower Revenue (HR)

Objective 3: Improve the 'Environment';

(7) River Flows (RF)

Objective 4: Maintain 'Supply Sustainability';

(8) Total System Minimum Storage (MS)

A popular outranking method will be used to compare the alternative operating rules. The alternatives will be compared two at a time, based on the values of the above PMs.

During the interview survey, we will request you to provide two types of information, which are required as inputs to the outranking method. They are:

1. Relative importance of PMs (expressed by Weights) and
2. Level of preference within each PM (expressed by a '**Preference Function'** which will be explained during the interview).

Information 1 (Inter-criteria): Weights

Your expression of the relative importance of the PMs will be facilitated by a simple procedure. The procedure uses a set of cards; each carrying the name of a performance measure. We will request you to lay them on a table and rank them indicating the order of importance that you assign to them by moving the cards around. Further information will be provided to you at the interview session.

Information 2 (Intra-criteria): Preference Function

Within a particular PM the relative preference of one potential value to another can be expressed by a Preference Function. We aim to identify a preference function for each performance measure listed previously.

A typical PF is shown in Figure 1. Further explanation of the PF will be provided at the interview session.

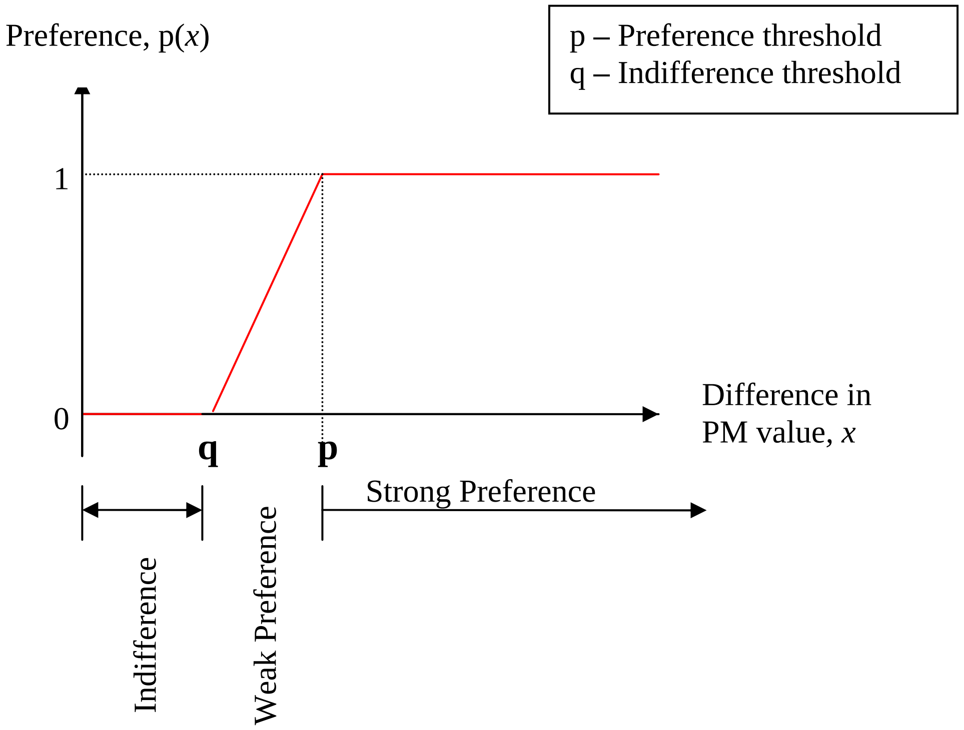


Figure E2-1: Preference Function

q – Represents the largest difference of PM value that is considered as negligible.
p – Represents the smallest difference of PM value that is considered as decisive.

Each PM could have a different PF, by defining its two parameters, ‘q’ and ‘p’.

Example –

A hypothetical example where the system performance is evaluated by eight PMs under three alternative operating rules is shown in Table 1. You may notice that it is hard to decide which alternative is superior to others, without knowing our tolerance levels on these PMs.

Table E2-1: Evaluation of Alternatives based on PM values (All values are arbitrary)

	Supply Reliability	Worst Restriction Level	Duration of Restrictions	Frequency of Restrictions	Pumping/ Treatment Costs	Hydropower Revenue	River Flow Volume	Total System Minimum Storage
Units	%		Months		$ mil./ year	$ mil./ year	GL/ year	1000 ML
Alternative 1	97	3	64	0.05	5.0	3.8	200	500
Alternative 2	95	4	87	0.08	3.5	4.5	230	650
Alternative 3	98	2	56	0.02	7.0	2.4	180	300

If we are to decide on a PF for 'Supply Reliability ', we need to decide a value for each of the parameters 'q' and 'p'.

Say, for 'Supply Reliability' if we think that up to a 3% difference between two reliability levels is negligible and when the difference is beyond 5% it is decisive (or substantial) ; we say q = 3 and p = 5. Then the PF for 'Supply Reliability' will be as shown in Figure 2.

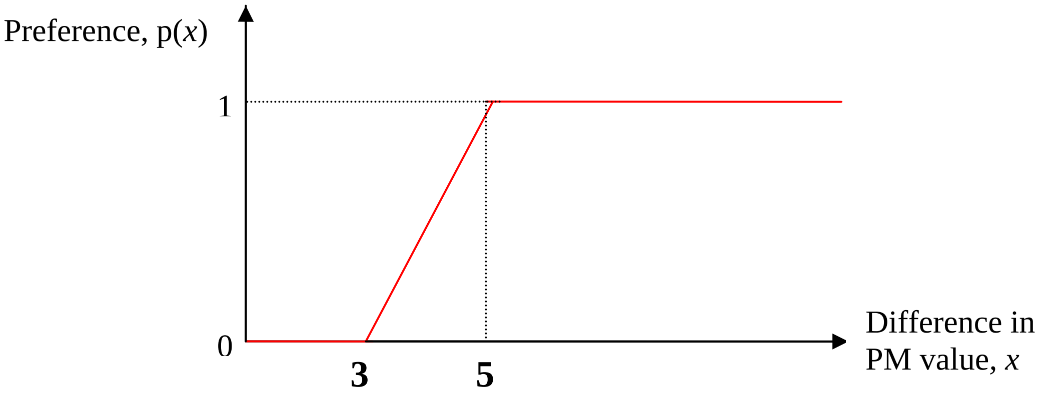


Figure E1-2: PF for Supply Reliability

To facilitate the association of a preference function to each PM, six specific shapes as shown in Figure 3 below are proposed by the authors of this pair-wise comparison method. Each shape depends on up to two thresholds; indifference threshold, ***q*****,** preference threshold**,** ***p*** and Gaussian threshold**,** ***s***. During the interview session, we will seek your opinion on the types of preference functions appropriate for various performance measures.

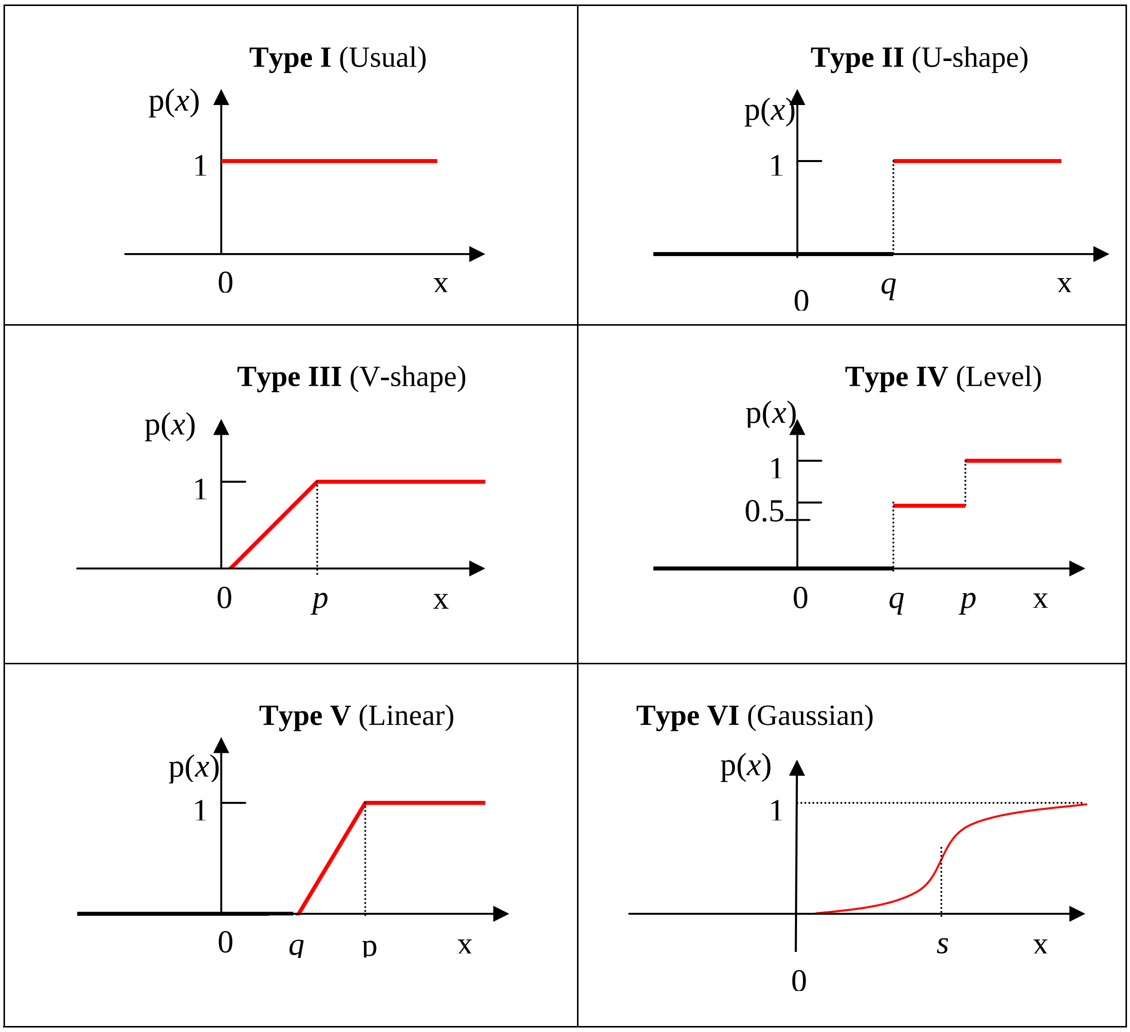


Figure E -3: Generalised Preference Function Types

Note: Types I, II and III can be considered as a subset of Type V and also the preferences of most PMs can be represented by a Type V curve

****

Appendix F: Questionnaire - Survey with Water Users and Environmentalists

Preferences on Water Use – Customer Survey

Please tick the boxes where appropriate.

(Q1) To which of the following age groups do you belong?

18 - 24 ☐
25 – 34 ☐
35 – 49 ☐
50 – 59 ☐
60+ ☐

(Q2) Record the gender
Male ☐
Female ☐

(Q3) Who is your retail Water Company?

City West Water ☐
South East Water ☐
Yarra Valley Water ☐

(Q4) To which customer category do you belong?

Residential ☐
Industrial / Commercial ☐
Any other (please specify) ☐

In responding to the following questions, please try to express your views on having a fair (as you think how it should be) balance between the following;

- **a water supply with minimum restrictions**
- **an affordable price for water**
- **more water released to waterways (a healthy eco-system)**
- **more water saved for the future**

We all know that water is a scarce and a valuable resource. So, it is clear that an improvement of any of these would come with an impact on the others.
For example, accepting the restrictions to a certain extent would mean that we have;
- more water saved for future use,
- more water for animals & plants in and around waterways
and - a reasonable price for water.

For long term planning purposes of the Water Supply System, we have defined an overall goal.

Overall Goal

‘To ensure a safe and reliable water supply at an acceptable cost and in an environmentally sensitive manner for the benefit of the present and future Melbournians.’

(Q5) Do you agree with the above goal?

Totally agree ☐
Partly agree ☐
Do not agree ☐

Water Restrictions (Duration & Reliability of supply)

(Q6) On imposing water restrictions, my desire is to;

Accept it to some extent ………… Go to (**Q7**)
Prefer no restrictions ………… Go to (**Q8**)
Strongly oppose restrictions ………… Go to (**Q10**)

(Q7) The operating rules for the water supply system could be designed to have different ‘**durations**’ of restrictions of varying severity, depending on how much water we want to save for future use. Indicate the time duration (at a stretch) that you think is most reasonable to have water restrictions at each restriction level.
(Please refer to the Attachment 1 to see how the different Stages of restrictions affect different purposes.)

	0 months	3 months	6 months	1 year	2 years	3 years	Other (pl. specify)
Stage 1							
Stage 2							
Stage 3							
Stage 4							

(Q8) What is the approximate duration (at a stretch), beyond which you do not wish (strongly oppose) to have any kind of (even Stage 1) restriction?

3 months	6 months	1 year	2 years	3 years	Other (pl. specify)

(Q9) Reliability of Supply (Maximize)

Indicate your preferences on the % time with an unrestricted supply (tick preference levels; what you prefer a lot, what is acceptable and what level it shouldn’t go beyond).

	Most preferred	Acceptable	Strictly not less than
More than 91% (~ >11 months / yr)			
90% - 76% (~ 9 -11 months / yr)			
75% - 51% (~ 6 – 9 months / yr)			
50% - 25% (~ 3 – 6 months / yr)			
Below 25% (~ < 3 months / yr)			

(Q10) Level of Restrictions (Minimize)

Different stages of restriction impose varying levels of severity on watering gardens, vehicle washing etc.(Please refer to the Attachment 1 to see how the different Stages of restrictions affect different purposes.)
In general, how do you feel about these different Stages of restriction?

	Very Lenient	Quite Lenient	Acceptable	Quite Harsh	Extremely Harsh
Stage 1					
Stage 2					
Stage 3					
Stage 4					

For **(Q11)** to **(Q15)**, indicate the levels at which you would personally feel satisfied about the measure indicated in bold letters (Tick preference levels; what you prefer a lot, what is acceptable and what level it shouldn't go beyond).

(Q11) Frequency of Restrictions (Minimize)

Water restrictions can occur in the future, as a part of responding to drought conditions. Depending on how much water we want to save for future, the operating rules could be designed to have restrictions at different '**frequencies**'. Indicate your preferences on the following frequencies, assuming Stage 1 restrictions of at least 3 months duration.

	Most preferred	Acceptable	Strictly not more than
No restrictions (0% chance annually)			
Once in 10 years(10% chance annually)			
Once in 5 years (20% chance annually)			
Once in 3 years (~33% chance annually)			
≥ Every year (≥ 100% chance annually)			

For questions **(Q12)** to **(Q15)**, if you do not wish to indicate your preferences with the available information, you may tick only the 'As necessary' box.

(Q12) River Flows (Maximize)

Currently the minimum environmental flow volumes are released to the waterways to ensure there is enough water for fish, other wildlife and plants. Indicate your preferences on the **amount of water released to our waterways**.

☐ As necessary

	Most preferred	Acceptable	Strictly not less than
High flows			
Moderate flows			
Minimum requirements			
Below minimum requirement			
No water released to waterways			

(Q13) Pumping / Treatment Costs (Minimize)

At times of significant drought periods, sometimes water is pumped from Yarra River to Sugarloaf reservoir as a supplement to the supply. This of course will result in less water flow in the river and accompany some additional costs to all of us.
Indicate your preferences on the **amount of pumping** that should occur.

☐ As necessary

	Most preferred	Acceptable	Strictly not more than
No pumping			
Minimal pumping			
Small amounts			
Moderate amounts			
Large amounts			

(Q14) Hydropower Generation (Maximize)

It is possible to generate hydropower at Thomson reservoir and Cardinia reservoir through the hydropower stations, depending on the storage levels. Though this can bring additional revenue to water authorities, the current policy is the 'minimum power generation' with the water that is surplus to Melbourne's needs.
Indicate your preferences on the **amount of hydropower generated.**

☐ As necessary

	Most preferred	Acceptable	Strictly not less than
Large amounts			
Moderate amounts			
Small amounts			
Minimal power generation			
No power generation			

(Q15) Minimum Storage of the Reservoirs (Maximize)

Thinking of saving water for future use, indicate your preferred **minimum water levels in our storage reservoirs**. To get an idea, the storage levels (as a % of the total storage) at which we enter different stages of restriction, for each month is given in the Attachment 2 (normally between 45%-55% range we enter Stage 1 restrictions).

☐ As necessary

	Most preferred	Acceptable	Strictly not less than
Over 95% full (> 3 years' supply)			
65% full (~ 2 years' supply)			
50% full (~ 18 months' supply)			
30% full (~ 1years' supply)			
Below 30% full (< 1 years' supply)			

Weights Assessment

To assess the performance of the Melbourne water supply system, we have identified 8 key Performance Measures that fall under four broad objectives.
They are:

Related to ‘ Level of Service ’:

(1) Total Number of Months with Restrictions (RM)
(2) Worst Restriction Level (WL)
(3) Duration of Restrictions (DR)
(4) Frequency of Restrictions (FR)

Related to ‘ Costs / Revenues ‘:

(5) Pumping / Treatment Costs (PC)
(6) Hydropower Revenue (HR)

Related to ‘ Environment‘:

(7) River Flows (RF)

Related to ‘Supply Sustainability’:

(8)Total System Minimum Storage (MS)

(a) Weights Assessment on PMs

Each of the eight cards has the name of a PM written on it. A small explanatory note is also given on the back of each card.

Step 1
Place them in a row on a flat surface, in the order of importance that you assign to them, starting with the most important one. (The cards with equally important measures may be grouped together.)

Step 2
Insert in between any white cards given to you, to express the gaps in importance. The greater the difference between the importance, the greater the number of white cards will be.

Record the pattern on the line given below. The first one is the most important measure and the last one is the least important measure.

Most Important ------------↓------------↓------------↓------------↓------------↓------------↓------------↓------------ **Least Important**

No. of Blank cards ☐ ☐ ☐ ☐ ☐ ☐ ☐

(Q16) How many times the most important factor is more important than the least important one?

(b) Weights Assessment on Higher Level Objectives

Repeat the procedure in (a), *(Step 1 & Step 2)* for the four cards representing the broad objectives; ‘Level of Service’, ‘Costs / Revenues’, ‘Environment’ and ‘Supply Sustainability’.

Record the pattern.

Most Important --- **Least Important**

No. of Blank cards ☐ ☐ ☐

(Q17) How many times the most important category is more important than the least important one?

Attachment 1

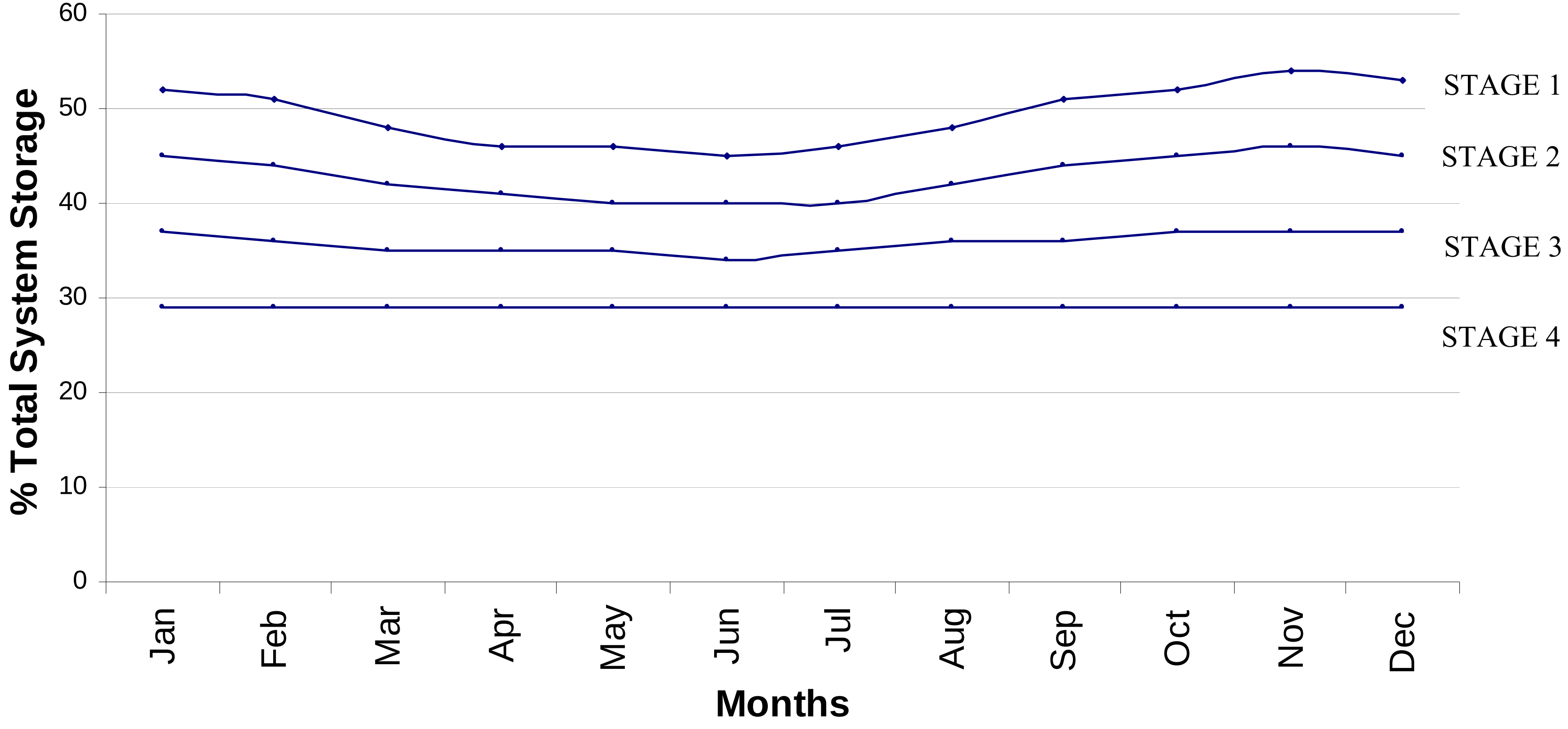
Water Restrictions

PURPOSE	STAGE OF RESTRICTION	RESTRICTION
Private Gardens	**One**	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Two	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand watering of garden beds 6 -8 am and 8-10 pm, every second day
	Four	• Buckets only may be used to water shrubs and trees
Public Gardens	**One and Two**	• Hand watering and sprinklers any time • Automatic sprinklers 11 pm-6 am
	Three	• No lawn watering • Hand and sprinkler watering of garden beds 6-8 am and 8-10 pm • Automatic sprinklers 11 pm-6 am
	Four	• Buckets only may be used to water shrubs and trees
Swimming Pools	**One and Two**	• Topping up allowed • New pools require prior written authority
	Three	• Topping up allowed using only a hand held hose • New pools require prior written authority
	Four	• Topping up allowed using only a bucket • New pools require prior written authority

Sports Ground	**One**	• Hand watering and sprinklers 6 - 8 am and 8 – 10 pm • Automatic sprinklers 11 pm – 6 am
	Two	• Only the ‘active’ playing areas to be watered and then only by: - Hand watering and sprinklers 6-8 am AND 8-10 pm - Automatic sprinklers 1 pm-6 am
	Three	• Only the ‘active’ playing areas to be watered and then only by: - Bucket - Hand held hose if for professional sport
	Four	• Only the ‘active’ playing areas to be watered and then only by bucket or hand held hose if for professional sport. Prior written authority required.
Industry	**One, Two, Three and Four**	• No restrictions
Commercial Garden or Nursery	**One, Two and Three**	• Hand watering and sprinklers 6-8 am and 8-10 pm • Automatic sprinklers 11 pm – 6 am
	Four	• Only by prior written authority
Vehicles	**One**	• Trigger hose only
	Two	• Bucket only
	Three and Four	• Not permitted
Paved Areas	**One, Two, Three and Four**	• Not permitted
Windows	**One, Two and Three**	• Only by using a bucket can filled directly from a tap
	Four	• Not permitted

Restriction Entry Trigger Points

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stage 1	52	51	48	46	46	45	46	48	51	52	54	53
Stage 2	45	44	42	41	40	40	40	42	44	45	46	45
Stage 3	37	36	35	35	35	34	35	36	36	37	37	37
Stage 4	29	29	29	29	29	29	29	29	29	29	29	29



Appendix G1: Survey Results - Resource Manager (RM) Group

RM Identification No.	Goal			Preference Functions on Performance Measure (PMs)								Weights Assessment on PMs*	Relative Range on PMs	Weights Assessment on Objectives* LS - Level of Service A - Affordability E - Environment SS - Supply Sustainability	Relative Range on Objectives
	Totally agree	Partly agree	Do not agree	Supply Reliability (SR)	Worst Restriction Level (WL)	Duration of Restrictions (DR)	Frequency of Restrictions (FR)	Pumping / Treatment Costs (PC)	Hydropower Revenue (HR)	River Flows (RF)	Total System Min. Storage (MS)				
				LS				A		E	SS	← Most Important Least Important →		← Most Important Least Important →	
1	x			Type I	Type I	Type V q = 4 p = 8	Type V q = 0.06 p = 0.1	Type V q = 1 p = 2	Type V q = 0.15 p = 2.15	Type I	Type III q = 0 p = 90	WL 3 DR 2 FR 0 SR 0 MS 2 RF 3 PC 0 HR	100	LS 0 SS 0 CR 0 E	100
2	√			Type II q = 2	Type VI s = 2	Type II q = 6	Type II q = 0.067	Type II q = 3	Type II q = 1	Type I	Type V q = 270 p = 450	RF 0 DR 0 SR 0 HR WL FR MS PC	1.5	LS 0 E 0 CR 0 SS	1.5
3	√			Type III p = 5	Type III p = 3	Type III p = 12	Type V p = 0.2 q = 0.1	Type V q = 1 p = 5	Type III p = 3.6	Type III p = 80	Type IV q = 92 p = 184	MS 1 WL 1 RF 0 FR 0 SR 1 DR 1 PC 0 HR	50	SS 1 E 0 CR LS	100
4	√			Type II q = 5	Type II q = 3	Type II q = 10	Type V p = 0.2 q = 0.05	Type V q = 2 p = 6	Type V q = 0.2 p = 3.2	Type III p = 80	Type III p = 50	MS 1 FR 2 WL 1 RF 2 PC 0 HR 0 SR 0 DR	5	SS 3 E 1 CR 1 LS	4
5	√			Type II q = 5	Type II q = 2	Type II q = 12	Type II q = 0.2	Type I _	Type II q = 1.9	Type II q = 80	Type II q = 39	WL 1 DR 0 SR 0 FR 1 PC 1 MS 0 HR 1 RF	100	LS 0 CR 1 SS 1 E	100
6	√			Type II q = 5	Type II q = 3	Type II q = 12	Type II q = 0.06	Type II q = 2	Type II q = 1.9	Type II q = 30	Type I	MS 0 SR 1 DR 1 FR 1 WL 1 PC 1 HR RF	50	SS 1 LS 2 CR E	20

Note:

* The numerical value in between the PMs or objectives indicate the number of blank cards

Appendix G2: Preference Thresholds (*p* & *q* Values) - Water User (WU) Group

Serial No.	Supply Reliability (Max.)				Worst Restriction Level (Min.)				Duration of Restrictions (Min.)				Frequency of Restrictions (Min.)				Pumping / Treatment Costs(Min.)					Hydropower Revenue (Max.)					River Flows (Max.)					Minimum Storage (Max.)				
	Upper Limit = 100%				Upper Limit = 0				Upper Limit = 0 months				Upper Limit = 0				Upper Limit = 0 $mil/yr					Upper Limit = 5 $mil/yr					Upper Limit = 320 Gl/year					Upper Limit = 1773 Gl				
	Acceptable	Strictly not less than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value
WU1	12.5	12.5	-12.5	-12.5	3	4	3	4	24	24	24	24	0.3	1	0.3	1		2	2	2	2		4.6	4.55	-4.6	-5		160	80	-160	-80		887	532	-887	-532
WU2	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1		4	4	4	4		3.7	3.70	-3.7	-4		240	240	-240	-240		1596	1596	-1596	-1596
WU3	82.5	12.5	-82.5	-12.5	3	4	3	4	120	120	120	120	0.1	1	0.1	1		2	2	2	2		2.9	2.85	-2.9	-3		240	160	-240	-160		1152	887	-1152	-887
WU4	12.5	12.5	-12.5	-12.5	4	4	4	4	NA	NA			1	1	1	1	1	_	_				2.9	0.00	-2.9	0		240	240	-240	-240	1	_	_		
WU5	AN	AN			4	4	4	4	NA	NA			AN	AN			1	_	_			1	_	_			1	_	_				1596	1152	-1596	-1152
WU6	62.5	37.5	-62.5	-37.5	4	4	4	4	6	24	6	24	0.3	1	0.3	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU7	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1		2	4	2	4		0	0.00	0	0		240	160	-240	-160	1	_	_		
WU8	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	NA	NA			1	_	_			1	_	_			1	_	_			1	_	_		
WU9	82.5	62.5	-82.5	-62.5	2	3	2	3	120	120	120	120	0.2	0.2	0.2	0.2		2	2	2	2		5.4	3.70	-5.4	-4		240	160	-240	-160		1152	887	-1152	-887
WU10	82.5	62.5	-82.5	-62.5	3	4	3	4	24	24	24	24	0.3	0.33	0.3	0.3		6	6	6	6		3.7	3.70	-3.7	-4		160	160	-160	-160		887	887	-887	-887
WU11	62.5	37.5	-62.5	-37.5	4	4	4	4	6	120	6	120	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU12	62.5	12.5	-62.5	-12.5	3	4	3	4	12	120	12	120	0.2	1	0.2	1	1	_	_				5.4	3.70	-5.4	-4		240	160	-240	-160		1152	532	-1152	-532
WU13	82.5	82.5	-82.5	-82.5	4	4	4	4	12	12	12	12	1	1	1	1		4	4	4	4	1	_	_				240	160	-240	-160	1	_	_		
WU14	62.5	37.5	-62.5	-37.5	2	3	2	3	12	12	12	12	0.3	1	0.3	1		2	4	2	4		2.9	0.00	-2.9	0		160	80	-160	-80		887	532	-887	-532
WU15	82.5	62.5	-82.5	-62.5	4	4	4	4	6	120	6	120	0.3	1	0.3	1	1	_	_				3.7	2.85	-3.7	-3	1	_	_				887	532	-887	-532
WU16	12.5	12.5	-12.5	-12.5	2	3	2	3	120	120	120	120	1	1	1	1	1	_	_			1	_	_				160	0	-160	0		1152	887	-1152	-887
WU17	62.5	12.5	-62.5	-12.5	3	4	3	4	12	12	12	12	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU18	37.5	12.5	-37.5	-12.5	2	3	2	3	120	120	120	120	0.3	1	0.3	1	1	_	_			1	_	_			1	_	_				887	532	-887	-532
WU19	82.5	62.5	-82.5	-62.5	3	4	3	4	NA	NA			1	1	1	1	1	_	_				0	0.00	0	0		240	80	-240	-80		887	887	-887	-887
WU20	62.5	12.5	-62.5	-12.5	1	2	1	2	3	6	3	6	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU21	62.5	37.5	-62.5	-37.5	3	4	3	4	0	6	0	6	0.1	1	0.1	1	1	_	_			1	_	_			1	_	_				1152	1152	-1152	-1152
WU22	37.5	12.5	-37.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU23	37.5	12.5	-37.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU24	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_				240	160	-240	-160		532	532	-532	-532
WU25	37.5	37.5	-37.5	-37.5	4	4	4	4	3	3	3	3	NA	NA				6	6	6	6		4.6	4.55	-4.6	-5		240	240	-240	-240		_	_		
WU26	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	0.3	0.33	0.3	0.3		4	8	4	8	1	_	_			1	_	_				887	266	-887	-266
WU27	37.5	12.5	-37.5	-12.5	4	4	4	4	24	120	24	120	0.3	1	0.3	1		4	4	4	4		4.6	3.70	-4.6	-4		240	160	-240	-160	1	_	_		
WU28	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	0.3	1	0.3	1		2	2	2	2		3.7	3.70	-3.7	-4	1	_	_				1152	1152	-1152	-1152
WU29	12.5	12.5	-12.5	-12.5	2	3	2	3	24	24	24	24	1	1	1	1	1	_	_			1	_	_			1	_	_				887	266	-887	-266
WU30	12.5	12.5	-12.5	-12.5	3	4	3	4	12	12	12	12	1	1	1	1		4	6	4	6		2.9	0.00	-2.9	0	1	_	_			1	_	_		
WU31	82.5	37.5	-82.5	-37.5	4	4	4	4	12	12	12	12	0.3	0.33	0.3	0.3	1	_	_			1	_	_				160	160	-160	-160	1	_	_		
WU32	95	62.5	-95	-62.5	4	4	4	4	12	12	12	12	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU33	12.5	12.5	-12.5	-12.5	2	3	2	3	6	120	6	120	0.3	0.33	0.3	0.3		6	8	6	8		4.6	4.55	-4.6	-5		160	0	-160	0		887	266	-887	-266
WU34	12.5	12.5	-12.5	-12.5	4	4	4	4	6	6	6	6	1	1	1	1		6	6	6	6		4.6	4.55	-4.6	-5		240	240	-240	-240		887	887	-887	-887
WU35	62.5	12.5	-62.5	-12.5	3	4	3	4	12	24	12	24	0.3	1	0.3	1		4	8	4	8		2.9	2.85	-2.9	-3		160	0	-160	0		887	266	-887	-266
WU45	62.5	12.5	-62.5	-12.5	4	4	4	4	0	12	0	12	0.3	1	0.3	1		4	8	4	8		2.9	2.85	-2.9	-3		240	0	-240	0		887	266	-887	-266
WU46	95	95	-95	-95	1	2	1	2	0	6	0	6	0.1	1	0.1	1	1	_	_			1	_	_				240	240	-240	-240		1152	887	-1152	-887
WU47	37.5	37.5	-37.5	-37.5	3	4	3	4	120	120	120	120	0.2	0.2	0.2	0.2		4	8	4	8		4.6	4.55	-4.6	-5		320	320	-320	-320		887	532	-887	-532
WU48	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		2	2	2	2		4.6	4.55	-4.6	-5		320	320	-320	-320		1152	1152	-1152	-1152

Serial No.	Supply Reliability (Max.)				Worst Restriction Level (Min.)				Duration of Restrictions (Min.)				Frequency of Restrictions (Min.)				Pumping/Treatment Costs(Min.)					Hydropower Revenue (Max.)					River Flows (Max.)					Minimum Storage (Max.)				
	Upper Limit = 100%				Upper L. = 0				Upper L. = 0 months				Upper L. = 0				Upper L. = 0 $mil/year					Upper L. = 5 $mil/year					Upper L. = 320 Gl/year					Upper L. = 1773 Gl				
	Acceptable	Strictly not less than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value
WU49	12.5	12.5	-12.5	-12.5	2	3	2	3	120	120	120	120	0.3	1	0.3	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU50	95	95	-95	-95	4	4	4	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_				1152	1152	-1152	-1152
WU51	37.5	37.5	-37.5	-37.5	4	4	4	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_				0	0	0	0	1	_	_		
WU52	NA	NA			3	4	3	4	12	120	12	120	1	1	1	1	1	_	_				2.9	2.85	-2.9	-3	1	_	_				887	887	-887	-887
WU53	62.5	62.5	-62.5	-62.5	NA	NA			6	120	6	120	0.1	0.1	0.1	0.1	1	_	_			1	_	_			1	_	_			1	_	_		
WU54	NA	NA			4	4	4	4	120	120	120	120	0.3	0.33	0.3	0.3	1	_	_			1	_	_			1	_	_			1	_	_		
WU55	12.5	12.5	-12.5	-12.5	2	3	2	3	6	6	6	6	0.2	1	0.2	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU56	37.5	12.5	-37.5	-12.5	3	4	3	4	12	12	12	12	0.1	1	0.1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU57	12.5	12.5	-12.5	-12.5	3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU58	37.5	12.5	-37.5	-12.5	2	3	2	3	0	0	0	0	0.1	1	0.1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU59	37.5	12.5	-37.5	-12.5	4	4	4	4	12	12	12	12	0.3	0.33	0.3	0.3		8	8	8	8	1	_	_			1	_	_				266	266	-266	-266
WU60	37.5	12.5	-37.5	-12.5	1	2	1	2	0	12	0	12	1	1	1	1	1	_	_			1	_	_			1	_	_				1152	266	-1152	-266
WU61	37.5	12.5	-37.5	-12.5	4	4	4	4	12	24	12	24	1	1	1	1	1	_	_			1	_	_			1	_	_				887	266	-887	-266
WU62	37.5	12.5	-37.5	-12.5	4	4	4	4	24	24	24	24	1	1	1	1		4	8	4	8		3.7	0.00	-3.7	0		160	0	-160	0		887	266	-887	-266
WU63	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1	1	_	_				4.6	4.55	-4.6	-5	1	_	_			1	_	_		
WU64	95	95	-95	-95	4	4	4	4	24	120	24	120	0	0	0	0	1	_	_			1	_	_			1	_	_			1	_	_		
WU65	37.5	12.5	-37.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		6	8	6	8		2.9	2.85	-2.9	-3		320	320	-320	-320		266	266	-266	-266
WU66	95	12.5	-95	-12.5	4	4	4	4	120	120	120	120	0	0	0	0	1	_	_			1	_	_			1	_	_			1	_	_		
WU67	NA	NA			3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_				320	320	-320	-320		1152	1152	-1152	-1152
WU68	62.5	37.5	-62.5	-37.5	4	4	4	4	120	120	120	120	1	1	1	1		2	4	2	4		0	0.00	0	0		320	320	-320	-320		1152	1152	-1152	-1152
WU69	82.5	62.5	-82.5	-62.5	4	4	4	4	12	24	12	24	0.2	0.33	0.2	0.3	1	_	_			1	_	_			1	_	_			1	_	_		
WU70	62.5	12.5	-62.5	-12.5	2	3	2	3	6	6	6	6	0.3	0.33	0.3	0.3		6	6	6	6		4.6	4.55	-4.6	-5		320	0	-320	0		887	887	-887	-887
WU71	NA	NA			4	4	4	4	120	120	120	120	1	1	1	1		2	2	2	2		2.9	2.85	-2.9	-3		320	320	-320	-320	1	_	_		
WU72	62.5	12.5	-62.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		2	2	2	2	1	_	_			1	_	_				1152	1152	-1152	-1152
WU73	37.5	37.5	-37.5	-37.5	2	3	2	3	120	120	120	120	1	1	1	1		6	8	6	8		2.9	0.00	-2.9	0		160	0	-160	0		887	266	-887	-266
WU74	37.5	37.5	-37.5	-37.5	2	3	2	3	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_				887	266	-887	-266
WU75	37.5	37.5	-37.5	-37.5	4	4	4	4	12	120	12	120	0.3	0.33	0.3	0.3	1	_	_			1	_	_			1	_	_			1	_	_		
WU76	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	0.3	0.33	0.3	0.3		6	8	6	8		3.7	0.00	-3.7	0		80	0	-80	0		1596	266	-1596	-266
WU77	12.5	12.5	-12.5	-12.5	4	4	4	4	12	120	12	120	1	1	1	1	1	_	_			1	_	_			1	_	_				1152	1152	-1152	-1152
WU78	12.5	12.5	-12.5	-12.5	2	3	2	3	120	120	120	120	1	1	1	1		4	4	4	4		2.9	0.00	-2.9	0		160	0	-160	0		887	266	-887	-266
WU79	NA	NA			3	4	3	4	120	120	120	120	1	1	1	1		4	8	4	8	1	_	_				80	80	-80	-80		266	266	-266	-266
WU80	82.5	12.5	-82.5	-12.5	4	4	4	4	6	6	6	6	1	1	1	1	1	_	_			1	_	_			1	_	_			1	_	_		
WU81	62.5	62.5	-62.5	-62.5	4	4	4	4	12	120	12	120	1	1	1	1		4	4	4	4		2.9	2.85	-2.9	-3		160	160	-160	-160		1152	887	-1152	-887
WU82	82.5	82.5	-82.5	-82.5	2	3	2	3	0	3	0	3	0.3	1	0.3	1		4	8	4	8		3.7	2.85	-3.7	-3	1	_	_				887	266	-887	-266
WU83	62.5	37.5	-62.5	-37.5	2	3	2	3	120	120	120	120	1	1	1	1	1	_	_				0	0.00	0	0	1	_	_				887	266	-887	-266
WU84	37.5	37.5	-37.5	-37.5	3	4	3	4	120	120	120	120	1	1	1	1	1	_	_			1	_	_			1	_	_				1152	1152	-1152	-1152
WU85	Skip		0	0	4	4	4	4	0	0	0	0	1	1	1	1	1	_	_			1	_	_			1	_	_				887	266	-887	-266
	SUM		-3175	-2000			234	275			4356	5640			47	61				128	172				-112	-84				-7520	-5040				-44064	-30232
	COUNT		70	70			75	75			73	73			73	73	44			32	32	42			34	34	41			35	35	29			46	46
	AVERAGE		-45.4	-28.6			3	4			60	77			0.7	0.8				4.0	5.4				-3.3	-2.5				-215	-144				-977	-663
	MODE		**-13**	**-12.5**			**4**	**4**			**120**	**120**			**1**	**1**				**4**	**8**				**-3**	**0**				**-240**	**-160**				**-887**	**-266**

AN - As necessary, NA - Not answered, * Not agreeing with the overall goal

Appendix G3: Preference Thresholds (*p* & *q* Values) - Environmentalist (EN) Group

Serial No.	Identification No.	Supply Reliability (Max.)				Worst Restriction Level (Min.)				Duration of Restrictions (Min.)				Frequency of Restrictions (Min.)				Pumping / Treatment Costs (Min.)					Hydropower Revenue (Max.)					River Flows (Max.)					Total System Minimum Storage (Max.)				
		Upper Limit = 100%				Upper Limit = 0				Upper Limit = 0 months				Upper Limit = 0				Upper Limit = 0 $mil/yr					Upper Limit = 5 $mil/yr					Upper Limit = 320 Gl/year					Upper Limit = 1773 Gl				
		Acceptable	Strictly not less than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not more than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value	As necessary	Acceptable	Strictly not less than	'q' Value	'p' Value
1	E01	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		2	2	2	2		3.7	3.7	-3.7	-3.7		240	240	-240	-240		1152	1152	-1152	-1152
2	E02	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		4	4	4	4		4.55	3.7	-4.6	-3.7		240	160	-240	-160		1152	1152	-1152	-1152
3	E03	12.5	12.5	-12.5	-12.5	4	4	4	4	120	120	120	120	1	1	1	1		4	8	4	8		4.55	3.7	-4.6	-3.7		240	160	-240	-160		887	532	-887	-532
4	E04	95.5	95.5	-95.5	-95.5	3	4	3	4	120	120	120	120	1	1	1	1		6	8	6	8		2.85	0	-2.9	0		160	0	-160	0		887	266	-887	-266
5	E05	NA	NA			4	4	4	4	120	120	120	120	1	1	1	1		2	8	2	8		4.55	0	-4.6	0		240	0	-240	0		1152	266	-1152	-266
6	E06	63	63	-63	-63	4	4	4	4	36	36	36	36	1	1	1	1		0	4	0	4		4.55	3.7	-4.6	-3.7		320	160	-320	-160		1152	887	-1152	-887
		SUM		-196	-196			23	24			636	636			6	6				18	34				-25	-15				-1440	-720				-6382	-4255
		COUNT		5	5			6	6			6	6			6	6	0			6	6	0			6	6	0			6	6				6	6
		AVERAGE		-39.2	-39.2			4	4			106	106			1.0	1.0				3.0	5.7				-4.1	-2.5				-240	-120				-1064	-709
		MODE		**-12.5**	**-12.5**			**4**	**4**			**120**	**120**			**1**	**1**				**2**	**8**				**-5**	**-4**				**-240**	**-160**				**-1152**	**-1152**