Stakeholder Preference Modelling In Multi-Objective Operation Of Urban Water Supply Systems – A Case Study On Melbourne Water Supply System

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EXTENDED ABSTRACT

Growing demands for water resources in urban areas coupled with possible adverse climate scenarios and the competition for additional water resources poses challenges to water resources managers. Conflicting objectives of the stakeholders intensify these challenges, requiring the consideration of multiple objectives in terms of social, economic, environmental and technical perspectives for long-term operation of urban water supply systems. Mathematical modelling has been widely used in the past for determining the optimum operating rules for water supply systems. These modelling approaches, ranging from simulation to stochastic optimisation have often addressed the decision problem with respect to a single objective. However, in reality, the decision problem is often associated with many (often-conflicting) objectives of the stakeholders. It is also emphasized that the decision making process for sustainable management of water resources should incorporate long-term economic, environmental and social equity considerations. Integration of these multiple objectives to evaluate the alternative operating rules for urban water supply systems can be accomplished effectively by multi-criteria decision aid methods, where modelling of stakeholder preferences plays an important role.

Recent protracted dry conditions across most of Victoria have highlighted the limited availability of water resources, particularly during drought periods. In order to manage water supply systems in the long and short term, a range of options exist, including demand management, alternative supplies, drought response initiatives, and the potential to optimise system operations. However an emerging issue is the extent to which stakeholder preferences can be included in the decision modelling process.

The work presented here is part of a research study to develop a Decision Support System (DSS) to assist in evaluating alternative operating rules for urban water supply systems. As a case study on Melbourne water supply system, this paper examines the preference modelling of three potential key stakeholder groups, viz. resource managers, water users and those representing environmental preferences groups. To facilitate the evaluation of system performance under the alternative operating rules, eight Performance Measures (PMs) were identified under four main objectives related to social, economic, environmental and system aspects. Stakeholder preferences were modelled using the multi-criteria decision aiding method, PROMETHEE (Preference Ranking and Organisation METHod for Enrichment Evaluation). The preference elicitation process comprised of an interviewer-assisted questionnaire survey to derive the preference functions and weights for the PMs as required by PROMETHEE and its computer software tool Decision Lab 2000. The survey was conducted on 97 personnel including 6 from Melbourne Water Corporation and 91 from Victoria University, representing a perceived categorisation of stakeholder groups. The paper also explains the formulation of the survey method, the structure of the questionnaire and how the results of the survey can be used in group decision-making.

The survey responses were used as a basis to model the preferences on PMs in terms of preference functions and weights. The revised Simos' Procedure, the technique used to collect information on weights, proved to be well accepted by the respondents. Modelling the preferences of resource managers was straightforward using the generalized preference function types described in PROMETHEE. A simplified approach was developed for other potential stakeholder groups who are not familiar with either the feasible ranges of the PM values or the generalized preference function types.

1. INTRODUCTION

Assessment of Long-term operational decisions of water supply systems is a challenging task requiring the consideration of multiple objectives in terms of social, economic, environmental and technical perspectives. Mathematical modelling has been widely used in the past for determining the optimum operating rules for water supply systems. These modelling approaches, ranging from simulation to stochastic optimisation have often addressed the decision problem with respect to a single objective. However, in reality, the decision problem is often associated with many (often-conflicting) objectives, which are not equally recognised by all stakeholder groups. Recently, community and stakeholder consultation has been seen as an essential component for sustainable management of water resources, both at strategic and operational levels (Water Resources Strategy Committee 2002). To illustrate the idea of stakeholder involvement in the form of group decision-making, the current study considered a hypothetical Decision Making Group (DMG) with representations from the stakeholder groups.

When the system performance of a water supply system is evaluated using a series of performance measures (PMs), choosing an optimum operating rule could be a complex decision problem for the DMs. Multi-Criteria Decision Aid (MCDA) assists the DMs in identifying trade-off solutions to these kinds of complex decision problems. Emphasizing the role of subjectivity in the decision process, it allows a fair compromise to be found between the objectives that can never all be satisfied at once (Pomerol and Barba-Romero 2000). However, in the context of MCDA, the stakeholder preference elicitation and modelling process is often seen as a complex task (e.g. Figueira and Roy 2002), involving a fair amount of time and effort.

Among the MCDA methods that consider the DM preferences, the utility-based methods and outranking methods have demonstrated their diversity through a vast range of applications. Over the past three decades, the theoretical framework of outranking methods has improved giving them a strong foundation and they are widely applied for major engineering related projects (e.g. Rogers et al. 2000). The outranking methods are based on a pair-wise comparison of alternatives and aggregating the preferences. ELECTRE III (ELimination Et Choix Traduisant la REalité) (Roy and Vanderpooten 1996) and PROMETHEE are two popular outranking methods that allow interactive learning. One of the most known and widely used outranking methods, PROMETHEE is chosen for this study, primarily because of its transparent computational procedure and simplicity (i.e. comparatively low time and effort required to reach a conclusion). There have been numerous engineering applications that recognise the transparency and simplicity of PROMETHEE (e.g. Georgopoulou et al. 1998).

The work presented here is part of a study to develop a Decision Support System based on PROMETHEE (Brans et al. 1986) and its computer software tool Decision Lab 2000 (Visual Decision 2003) to evaluate alternative operating rules for urban water supply systems. As a case study on the Melbourne water supply system, focusing on restriction rules, this paper highlights an indirect approach for stakeholder preference elicitation using an interviewer-assisted questionnaire survey on three potential stakeholder groups, viz. resource managers (RMs), water users (WUs) and those representing environmental preferences (ENs). It also illustrates how the information gathered was used to model the stakeholder preferences and how this information can be used in group decision-making.

2. PREFERENCE INFORMATION REQUIRED IN PROMETHEE

In addition to system performance data evaluated using a set of PMs for alternative operating rules, PROMETHEE requires modelling and incorporating the DM preferences, to analyse the problem. Preference modelling in PROMETHEE is facilitated by the following two types of information:

1. A preference function (PF) for each PM and
2. Weights (Relative importance of PMs).

2.1 Preference Function

In pair-wise comparison of alternatives, the preference function translates the deviation (x) between the values of a single PM, to a preference degree (or preference intensity), which will have a value between 0 and 1. 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 1. 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.

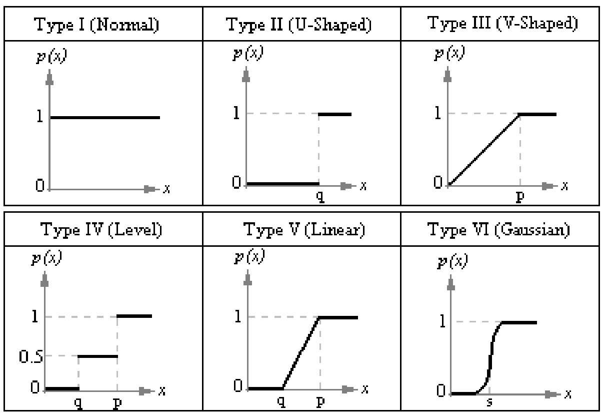

Figure 1. Generalized Preference Function Types

2.2 Weights

Often in MCDA, one PM is seen as more (or less) important than another. To express these differences, PROMETHEE requires for each DM, a set of weights (which indicate the relative importance of each PM in comparison to other PMs), $\{w_j, j=1,2,\ldots n\}$ for n 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 DMs 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.

3. PROBLEM FORMULATION

Melbourne Water (MW) operates and maintains a multi-reservoir system that provides water supplies to a population of about 3.5 million people in Melbourne. The current average annual water consumption for Melbourne is estimated at about 490,000 Ml. Melbourne's water supply system is shown schematically in Figure 2. It currently utilizes 10 major reservoirs including harvesting reservoirs and seasonal balancing storages. They have a total storage capacity of 1,773,000 Ml.

A limited volume of water is also pumped from the Yarra River into the Sugarloaf Reservoir and is fully treated to provide high quality water, at a higher operating cost. There are minimum environmental flow release requirements to be met for all harvested streams. A limited amount of hydropower is also 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. Melbourne's Drought Response Plan, developed by metropolitan water companies comprises a 4-stage demand restriction policy, which specifies progressive restrictions on outdoor water use depending on the total storage volume in the reservoirs. For this study, a set of alternative operating rules for the assessment by PROMETHEE was identified. The alternative rules include one variation each to: the demand restriction policy, amount of pumping from Yarra River, amount of hydropower to be generated and minimum river releases. Combining these four alternative operating rules with the corresponding 'current' operating rules provides some yields 16 alternative potential scenarios operating rules to be evaluated.

Long-term social, economic, environmental and technical aspects were taken into consideration when specifying the relevant objectives for this case study. A total of eight PMs that summarise the system performance under four broad objectives were identified. The details of the objectives and the corresponding PMs are given in Table 1. The PM values corresponding to each of the 16 operating rules were computed using the water supply planning and simulation model of the Melbourne system.

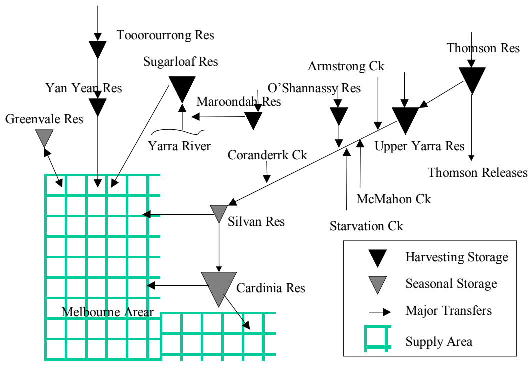

Figure 2. Melbourne Water Supply System

4. PREFERENCE ELICITATION AND MODELLING

In this study, obtaining preference information was facilitated by means of a specifically designed questionnaire interview procedure to collect the stakeholder preferences (i.e. PFs and weights for performance measures). Initially, the interview procedure was pilot-tested. Based on the findings of the pilot survey, the necessary adjustments and refinements were made to the questionnaire and the interview procedure before the full survey was carried out. Since the method requires the interviewer to meet the respondents in person to determine the weights of PMs, personal interview questionnaires with prepared questions were administered for eliciting preference information from the stakeholder groups.

The personal interview survey was conducted on a total of 97 personnel including 6 from MW and 91 from VU, representing the potential stakeholder groups. For this research case study, the stakeholder groups were represented by six MW staff (representing RM group) and six academic and post-graduates working on environmental sustainability represented the EN group.

The interviewing procedure and the questionnaire used for quantifying the preferences of WUs and ENs were the same, whereas a slightly modified but a more straightforward approach was used for RMs (as described later). The aim of the survey was made clear to the participants a few days in advance. It was also necessary to provide them with a good understanding of the definitions as well as the feasible ranges of the PM values. Interview procedure started with some simple demographic questions to help participants get started and become comfortable quickly.

Table 1. Objectives and Performance Measures

Objective	Performance Measure	Unit	Definition
Maximize level of service	PM1 - Monthly reliability of supply	%	Percentage of months with no restrictions to the total number of months in the simulation period
	PM2 - Worst restriction level	-	Worst stage of restriction reached during the simulation period
	PM3 - Duration of restrictions	Months	Maximum consecutive duration of any form of restrictions during the simulation period
	PM4 - Frequency of restrictions	-	Average annual chance of a restriction event during the simulation period
Minimize pumping & treatment costs / Maximize hydropower revenue	PM5 - Pumping / treatment costs	$mil / year	Average annual cost of pumping & treatment for the simulation period
	PM6 - Hydropower revenue	$mil / year	Average annual revenue from hydropower generation for the simulation period
Minimize the effects on environment	PM7 - River flows	Gl / year	Average annual total flow downstream of harvesting sites during the simulation period
Maximize supply sustainability	PM8 - Total system minimum storage	Gl	Minimum monthly total storage volume reached during the simulation period

4.1 Preference Function

It was aimed to derive a preference function for each PM given in Table 1 for each stakeholder representative. Two different approaches were used to derive PFs for (a) RMs and (b) WUs and ENs.

(a) Preference Functions for Resource Managers

Deriving PFs was considered to be quite straightforward with the RM group since they were well conversant with the definitions of PMs and their feasible range of values within the statutory requirements. In addition to the information provided to the other participants (i.e. WUs and ENs), the RMs were provided with 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*), prior to the interviews.

Some 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 instances where RMs either did not wish to use the direct method or were not familiar with all six types of PFs, an indirect method was adopted using only the PF Type V with its variants (Types I, II and III). Here, the RMs expressed a maximum difference in PM value that they would like to ignore in the feasible range till they did not feel a difference in the two alternatives (which 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 (which gave the value for '*p*'). For each RM, 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 PFs for the six RMs are presented in Table 2.

(b) PFs for Water Users and Environmentalists

In general the WUs and ENs were considered to be less familiar with either the actual values or the feasible ranges of certain PMs (e.g. PM5 - Pumping / treatment costs). Hence, the practicality of deriving PFs by the direct method as was done with the RMs was felt doubtful. Therefore, for these two groups, the interviewer was assisted with a structured questionnaire to elicit preference intensities on the PMs. The responses received were then used to derive PFs in an indirect way.

The questionnaire was prepared, assuming the PFs for these two stakeholders were modelled by a Type V curve with its variants for all PMs. The PMs, whose feasible ranges were familiar to the participants (i.e. PM1, PM2, PM3, PM4 and PM8), were defined by 5-point quantitative scales. All other PMs (i.e. PM5, PM6 and PM7) were defined by 5-point qualitative scales. 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 various preference levels in the 5-point scales were then fitted within the feasible range (in equal intervals) of the corresponding PM and a representative numerical value was assigned to each preference level, taking the base value as a reference point.

Typical answers received during the questionnaire survey on the preference intensities of PM1 and PM5 are presented in Figures 3 and 4 respectively. In order to derive the preference function for PM1, the middle value in the range was considered as the representative value. A similar procedure was adopted for other PMs with quantitative scales, i.e. PM2, PM3, PM4 and PM8. For the preference function for PM5, representative values were assigned to the qualitative values, which covered the entire range of feasible values.

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

Figure 3. WU and EN typical response for PM1

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

Figure 4. WU and EN typical response for PM5

A typical qualitative scale used for PM5 with their associated preference levels and representative numerical values are given in Figure 5. A similar procedure was adopted for other PMs with qualitative scales, i.e. PM6 and PM7.

Qualitative Scale	Preference Level	Representative Value ($mil/yr)
No pumping	Very high	0.0
Minimal pumping	High	2.0
Small amounts	Average	4.0
Moderate amounts	Poor	6.0
Large amounts	Very poor	8.0

Figure 5. WU and EN Qualitative Scale on PM5

Having received the responses from WUs and ENs for all eight PMs and converting their preference levels to numerical values as described above, it was possible to use this information to determine '*q*' and '*p*' values for each PM and for each participant. The value '*q*' is 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). 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 Figure 3, '*q*' = 100%-83% = 17% 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, $q = (4.0-0.0) = 4.0$ and $p = (6.0-0.0) = 6.0$ (Figures 4 and 5). The values derived as paired *q* and *p* values for PM1 (as an example), for 85 WUs and 6 ENs are graphically presented in Figures 6 and 7 respectively. For each combination of *p* (*x*-axis) and *q* (*y*-axis), a frequency, *n* is indicated (*z*-axis).

To illustrate the idea of group decision making in this study, it was decided to form a hypothetical DMG comprising all six RMs and one representation each from WUs and ENs. Therefore, it is necessary to obtain a single PF with its p and q values as the representation of each WU and EN group. Since paired *p* and *q* values were considered as 'categorical', the modal value was taken as the most representative for each PM. In the special case of every participant giving a different *p* and *q* combination for a PM (eg. PM5 for EN group), a random combination for *p* and *q* was chosen. For WUs and ENs the values of *p* and *q* automatically fixed the PF type (assuming Type V and its variants). The details of PFs are presented in Table 3.

Table 2. Preference Functions on Performance Measure (PM)s - Resource Manager Group

RM	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
1	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 p = 90
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
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
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
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
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

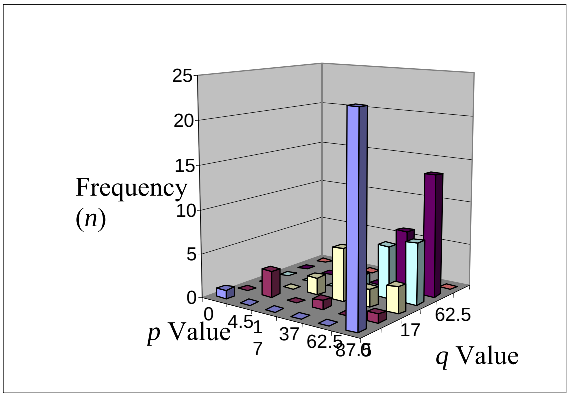

Figure 6. WU preference thresholds for PM1

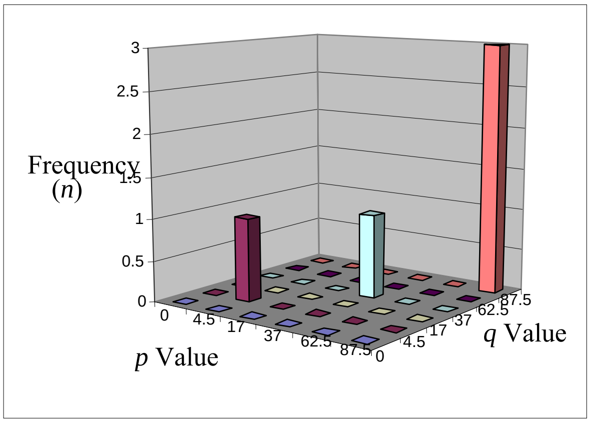

Figure 7. EN preference thresholds for PM1

4.2 Weights

Several methods have been proposed in the literature to estimate the weights of the PMs in outranking methods (Rogers et al. 2000). In contrast to the concept of PF, the concept of weights on PMs was considered to be more comprehensible to the participants and therefore a single method was used across all participants (i.e. RMs, WUs and ENs).

The weights in this study were derived using the 'Revised Simos' Procedure' of which the detailed calculation method is given in Figueira and Roy (2002). A distinct advantage of this weighting method was its ability to express the weighting preferences on an ordinal scale where most DMs find it easier to express their weightings on an ordinal scale rather than on a numerical scale (Rogers et al. 2000). The method uses three sets of 'playing cards' and a simple procedure, to determine the numerical values for the weights of PMs in an indirect way; the first set of cards (8 cards) carried a name of a PM on each of the cards, the second set of cards (4 cards) carried a description of an objective on each of the cards and the third set contained some blank cards.

The participants were first given the cards with PMs and requested to lay the cards on a table indicating the order of importance that they assign to the PMs by moving the cards around. Then they were asked to place any number of blank cards in between the PM cards to depict the gaps of importance. The question of '*How many times the most important PM is more important than the least important one?*' was asked and recorded as this is vital information for weights assessment. This procedure was then repeated for the set of cards with the objectives. Out of the two weight sets calculated for each respondent, it was assumed that he / she would have priority to address the importance of higher-level objectives. Therefore, a correction factor was applied to the PM weights based on the weights of the higher-level objectives. The frequency distributions of final weights on PM1 (as an example) calculated for WU and EN groups are given in Figures 8 and 9 respectively.

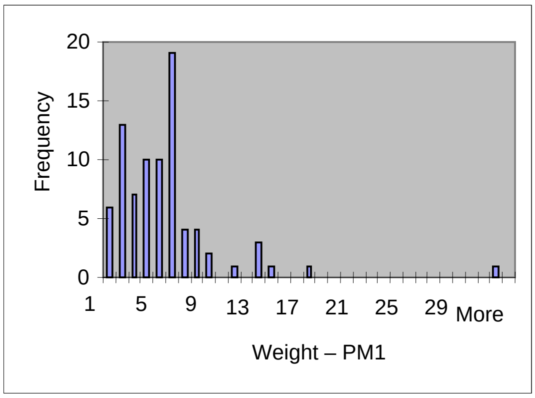

Figure 8. WU weights for PM1

To arrive at single representative weight values for WU and EN groups in forming the DMG, the median was considered as representative, since it agrees with the majority view (Hokkanen and Salminen 1994). One other advantage of the median is that it is not as sensitive to extreme values as the mean. The normalised weights on PMs thus derived for all the DMs in the DMG (6RMs, 1WU and 1EN) are shown in Table 4.

Table 3. Preference Functions on Performance Measure(PM)s

DM	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
WU	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
EN	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

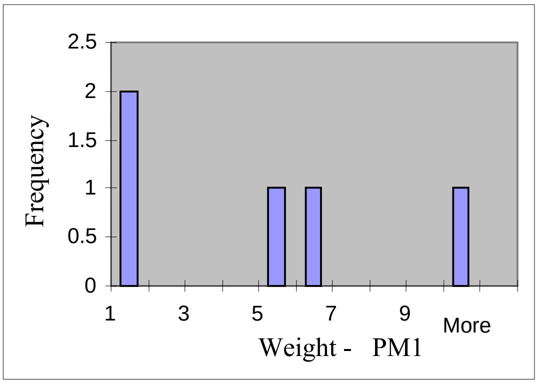

Figure 9. EN weights for PM1

Table 4. Normalised weights of PMs for all DMs

	Performance Measure (PM)							
	1	2	3	4	5	6	7	8
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	5	4	5	5	6	4	33	37
EN	5	4	5	4	1	5	40	37

5. SUMMARY AND CONCLUSIONS

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. This paper presented a detailed method for stakeholder preference elicitation and modelling, as required by PROMETHEE and Decision Lab 2000. The proposed approach, which is aided by an interviewer-assisted questionnaire survey, was demonstrated on three potential stakeholders of the Melbourne water supply system viz. Resource Managers (RMs), Water Users (WUs) and those representing Environmental interests (ENs).

Modelling preference intensities of the resource managers seemed to be straightforward using the generalized preference function types. However, a simplified approach was developed for other stakeholder groups who are not familiar with either the feasible ranges of the PM values or the generalized preference function types. The revised Simos' Procedure, the technique used to collect information on weights, proved to be well accepted by the respondents. The representative preference threshold values and the corresponding weight values for the three stakeholder groups were derived to be used in a group decision-making situation, as input parameters to Decision Lab 2000. This approach to preference modelling enables the evaluation and comparison of the alternative operating rules when PM values are available for each operating rule. This comparison will be covered in a forthcoming paper.

6. ACKNOWLEDGEMENTS

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