Development of a Decision Support Approach for Sustainable Urban Water Management

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Originality Statement

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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Elizabeth Lai

Abstract

The challenges of climate change, increasing population and drought have motivated water authorities around Australia to deliver water services more sustainably. Many of them have recently devised long-term water strategies using multi-criteria decision aid (MCDA) to assess their strategies. This thesis identified four shortcomings in the current practice of MCDA used in urban water management: (1) double counting, (2) judgement uncertainty, (3) interaction and (4) range sensitivity. The aim of this research was to account for these shortcomings, thereby aiding decision makers in their planning of more sustainable water strategies.

A decision support approach was developed to address the shortcomings, and utilised: (1) value focused thinking, to carefully structure the criteria value tree; (2) fuzzy sets, to account for uncertainty in decision makers' judgements on criteria weights and criteria scores; (3) the Choquet integral, to model interaction between criteria in conjunction with a linguistic preference elicitation technique; and (4) a novel technique to elicit criteria weights and to normalise criteria scores based on the concept of mitigation.

The developed framework was applied to an empirical case study, the Gold Coast Waterfuture project to illustrate the approach. This involved interviewing three groups of decision makers (DMs)—water users, water experts and water managers—to elicit their preferences in relation to different water strategies. The results obtained using the framework were closer to the decision makers' preferences, as compared to the conventional which neglects the identified shortcomings.

The main finding was that the selection of an appropriate preference model is critically related to the DMs' level of understanding of the decision problem. An averaging function can serve as a good initial approximation when no uncertainty is considered. More computationally demanding preference models which use fuzzy set theory and Choquet integral should only be used if the DMs have to make imprecise judgement with insufficient information and/or the DMs have a sufficient understanding of the interaction between the selected criteria. The practical application of this research is in providing decision makers with a stronger set of tools that include a modified and more rigorous MCDA which overcomes the shortcomings in the current practice.

Thesis Publications

Publications presented within this thesis:

Lai E., Lundie S. and Ashbolt, N.J. (2007). A new approach to aid urban water management decision making using trade-off sacrifice modelled by fuzzy logic. *Water Science and Technology* 56(8): 11-20.

Lai E., Lundie S. and Ashbolt, N.J. (2008). Review of multi-criteria decision aid for integrated sustainability assessment of urban water systems. *Urban Water Journal* 5(4): 315-327.

Lai E., Moore S., Lu J., Lundie S. and Ashbolt, N.J. (under review). Accounting for judgement uncertainties and double counting for urban water management decisions. *Water Resources Management*.

Lundie, S., Peters, G., Ashbolt, N., Lai, E. and Livingston, D. (2006) A sustainability framework for the Australian water industry. *AWA Water* 33 (7): 33-38.

Conference papers:

Lai, E., Lundie S. and Ashbolt, N.J. (2006). Assessing inter-relationships and decision support systems for integrated urban water sustainability assessment. In *Proceedings, 1st Australian Young Water Professionals Conference*, 15-17 February 2006, Sydney UNSW.

Lai, E., Lundie S. and Ashbolt, N.J. (2008). Fuzzy multi-criteria approach to assess the impacts of a tap water intervention for a rural community in Limpopo province, South Africa, *19th Multi-criteria Decision Making International Conference*, 2008, New Zealand University of Auckland.

Reports:

Lundie, S., Ashbolt N.J., Livingston, D., Lai E., Kärrman E., Blaikie J., Aderson J. (2006). Sustainability Framework: Methodology for Evaluating the Overall Sustainability of Urban Water Systems. *Sustainability Framework WSAA Occasional Paper No.17*. Melbourne, Water Services Association of Australia.

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Above all, I would like to dedicate this thesis as a testimony to God's faithfulness. The completion of this thesis has not been without trials and tribulations like all other doctoral studies, but the miracles that I experienced are what made this journey truly special. Challenges in the forms of physical illness, long distance supervision have all added to the burden on this journey but God faithfully provided in practical terms. His provision of dedicated physicians, timely advices from friends and family, financial support were all part His plan in drawing a conclusion to this journal.

Abbreviations

AA	arithmetic average
AFSAW	appropriated fuzzy simple additive weighting
AHP	analytical hierarchy process
ANP	analytical network process
CBA	cost-benefit analysis
CI	Choquet integral
DMs	decision makers
DSM	decision support methodologies
ELECTRE	ELiminiation Et Choix Traduisant la REalite
FCI	fuzzy Choquet integral
FMCDA	fuzzy multi-criteria decision aid
FSAW	fuzzy simple additive weighting
GA	geometric average
GCWF	Gold Coast Waterfuture
HA	harmonic average
IA	integrated assessment
LMED	Lukasiewicz median
MACBETH	Measuring Attractiveness by Categorical-Based Evaluation TecHnique
MADA	multiple attribute decision aiding
MAUT	multi-attribute utility theory
MAVT	multi-attribute value theory
MED	median
MCA	multi-criteria analysis
MCAP	multi-criterion aggregation procedure
MCDA	multi-criteria decision aid
MCDM	multi-criteria decision making
ML	megaliter
MODA	multiple objective decision aiding
OWA	ordered weighted averages
OWAent	ordered weighted average entropy
OWAopt	ordered weighted average optimistic
OWAorn	ordered weighted average orness

OWApes	ordered weighted average pessimistic
OWAqua	ordered weighted average quantifier
PMED	product median
PROMETHEE	Preference Ranking Organisation METHod for Enrichment Evaluations
PSM	problem structuring methods
SAW	simple additive weighting
SWARD	sustainable water-industry asset resource decisions
TBL	triple bottom line
TFN	triangular fuzzy number
TrFN	trapezoidal fuzzy numbers
UTA	utility theory additive
WA	weighted average
WMED	weighted median
WSAA	Water Services Association of Australia

Glossary

Calculated global value	The overall value associated with an alternative obtained from the aggregation of a preference model.
Crisp set	A set consisting all elements that can be classified uniquely to the set or its element, in which the degree of membership of any object in the set is either 0 or 1.
Criteria	The factors that may be used to make a judgement about the relative sustainability of a set of options.
Criteria weights	The elicited mitigation value trade-offs are directly taken as criteria weights.
Decision support approach	The structure process to assist DMs via identification stakeholders, selection criteria, selection of MCDA method and manipulation of recommendation.
Decision support methodologies	The second and the third stage (preference elicitation and modelling and aggregation) of a generic MCDA process.
Degree of membership	A value that represents membership in a fuzzy set which is defined over the range between 0 and 1 with 0 representing no membership and 1 representing absolute membership.
External uncertainty	Uncertainty related to the unknown consequences of action incurred by the external environment that is outside the control of the decision makers.
Fuzzy set	A set that contains elements having varying degrees of membership between 0 to 1 in the assertion that the elements belong to the set.
Global value	A value obtained from the value function for each alternative in order to establish a preference order for the alternatives.
Indicators	Measure the past and current values of specific criteria which can be used to benchmark future performances.
Internal uncertainty	Uncertainties that relate to the structure of the model adopted and the judgemental inputs.
Linguistic value	A term contains no nominal value, but simply a representation of knowledge.
Linguistic variable	A variable that contains a set of linguistic values that are not numbers but words or sentences instead of numerical values.
Mid-point technique	A technique to define value functions by eliciting reference points and mid-points from the users.
Mitigated normalising function	A novel technique to standardise criteria scores which is based on the mid-point evaluation technique.

Mitigation value trade-off	The new technique proposed by the author in making trade-offs that are based on the concept of mitigation.
Normalised criteria scores	Normalised criteria scores are the scores normalised using the normalised functions.
Normalising functions	Functions used to normalise raw criteria scores.
Observed global values	The study subject's rating of an alternative without using any decision support tool.
Partial value function	A function for assessing the performance value for a criterion with respect to an alternative.
Principles	The normative definitions or goals for sustainability.
Raw criteria scores	The original scores from the GCWF case study given by the advisory committee.
Reference points	The two ends points representing the worst and best value of the criteria measurement scale.
Rough set	An approximation of a crisp set in terms of a pair of sets which give the lower and the upper approximation of the original set.
Value functions	The underlying aggregation model constructed to represent DM's preference.
Value measurement theory	The chosen MCDA preference model for this thesis.
Value trade-offs	Making trade-offs that are based on measureable values.

Table of Contents

List of Tables

List of Figures

1 Introduction

1.1 Problem statement and research questions

Urban water systems have a number of functions including the provision of clean water to support a variety of uses, removal of wastewater from users for hygienic reasons and removal of stormwater to avoid flooding (Hellström *et al.*, 2000). The systems are traditionally characterised by centralised management and typically source water from large surface-water dams and distribute it via large pipes. With this conventional approach the capacity of the centralised system expanded to meet increasing demand. Bigger dams were built on rivers and more pipes were installed to transport water across long distances to the cities. However, despite the historical success of this 'big pipe' approach to manage the growth of modern cities, it is inefficient in meeting the ever-increasing demand and the current systems are reaching their new limits (World Commission on Dams, 2000).

At present, urban water systems are faced with a number of sustainability issues, such as the challenges of climate change, increasing population and drought (Vörösmarty *et al.*, 2000; Vlachos and Braga, 2001). It is becoming more difficult to guarantee the security of freshwater resources because Australia's rainfall and river flows are highly variable as a result of changes in climate overlaid on the already highly seasonal nature of river flows. The threat to secure freshwater is also compounded by the growth of urban sprawl in coastal cities and towns, where the majority of the people of Australia live and also the rest of the world live (State of Environment, 2006; Howe and Mitchell, 2011). This has placed an enormous amount of pressure on the urban water systems, accentuated by the increasing water demand. Furthermore, the prolonged drought experienced in Australia since 1996 has marked the declining levels of many major water storages (National Climate Centre, 2010). This was followed by the recent flood in Queensland during late December 2010 and early January 2011, further raised awareness on the possible impact of climate change.

With many major Australian cities reaching the limit of their current available water resources, opportunities exist to better manage the urban water systems through incorporating the concept of sustainability into decision making. These challenges have motivated water authorities around Australia to rethink how to deliver urban water services (Water Services Association of Australia, 2009). In seeking more sustainable water resource options, various authorities have devised water strategy plans for the next 50 years (Gold Coast Water, 2005; Gosford-Wyong Council's Water Authority, 2006; Goulburn Valley Water, 2007; Water Corporation, 2008; Government of South Australia, 2009; Brown *et al.*, 2010; Sydney Water Corporation, 2010).

The challenge in developing these strategies is to acknowledge the multi-faceted nature of sustainability, which includes not only human societal and economic needs, but also environmental and technological needs. Adequate frameworks are becoming increasingly important to help arrive at more sustainable solutions for urban water systems. The Millennium Ecosystem Assessment (2003) subprogram of the United Nations Environment Program highlighted the importance of better information for long-term sustainability and the importance of utilising sound scientific knowledge: "Better information cannot guarantee improved decisions, but it is a prerequisite for sound decision-making" (Millennium Ecosystem Assessment, 2003, p.1). Despite the call for incorporating sustainability into urban water management, there is a lack of knowledge of how to incorporate sustainability into the decision making process and how sustainability of various technical systems should be assessed (Hellström *et al.*, 2000; Loucks *et al.,* 2000). Water service providers are faced with increasing difficulty in balancing the multi-faceted issues involved in the sustainability of urban water management (Ashley *et al.*, 2004; Malmqvist *et al.*, 2006). More recently the realisation of the water-energy nexus has broadened the need for a system's view to achieving more sustainable water services (Novotny, 2011).

The sustainability of various water strategies are typically assessed using a multi-criteria problem which involves multiple attributes measuring a range of sustainability issues and a finite number of options. Multi-criteria decision aid (MCDA) is a popular tool among water authorities as it is suitable for dealing with such problems (Hajkowicz and Collins, 2007). A major role which MCDA plays is to enhance the users' understanding of the decision problem by explicitly describing trade-offs and aiding them in rationally and consistently articulating their values (Starkl and Brunner, 2004; Munda, 2005). However, there are limitations to the credibility of results obtained by multi-criteria approaches due to a number of reasons (Sharda *et al.*, 1988; Newman *et al.*, 2000). In particular, four shortcomings associated with the use of MCDA in urban water management were identified in this thesis. These shortcomings relate to: (1) poor problem framing in the selection of criteria resulting in double counting (Saaty, 1994a; Keeney, 1996; Odum, 1996; Costanza *et al.*, 1997; Searchinger *et al.*, 2009), (2) uncertainty in judgement given by decision makers (DMs) (Bellman and Zadeh, 1970; Ribeiro *et al.*, 1995; Zimmermann, 2000), (3) interaction between inter-depending criteria (Sugeno, 1974), and (4) the influence of criteria range on the assignment of criteria weights (Fischer, 1995). These shortcomings do not appear to be well addressed in the current practice of urban water management decisions.

This thesis describes the development of such a decision support approach that addresses the three identified shortcomings. A decision support approach is defined as the structured process to assist DMs via identification of stakeholders, selection criteria, selection of MCDA method and manipulation of recommendation. The aim is to improve the integrity of MCDA in supporting urban water management decision problems by answering the following questions:

- How to avoid *double counting* in urban water management decision problems?
- How to account for *judgement uncertainty* in urban water management decision problems?
- How to account for *criteria interaction* in urban water management decision problems?
- How to avoid *range sensitivity* in urban water management decision problems?

1.2 Research problems

The four identified shortcomings relate closely to the technical model of DMs' preference structure or their points of view. The associated issues may not be apparent at first sight. The following sections highlight each of these shortcomings briefly. Further details on the four identified shortcomings are provided in Section 2.5.

1.2.1 Double counting

Double counting occurs when the chosen criteria are at least partly redundant (Schankerman, 1981). Saaty (1994a) defined this problem as 'the occurrence or use of the weight of a criterion more than once in the weighting of the alternative'. For example, the two criteria: greenhouse gas emissions and primary energy use, double count the importance of non-renewable energy use. The impact of double counting is in the over-valuation of certain attributes of the decision making problems which in turn reduces the integrity of the analysed decision outputs. DMs may perceive the analysis outputs as contrary to their true preference, thus affecting the credibility of MCDA.

1.2.2 Judgement uncertainty

The process of decision making is filled with uncertainties that can arise from incomplete knowledge of the consequences of actions, imprecision, over simplification and inherent randomness (Bellman and Zadeh, 1970; French, 1995; Zimmermann, 2000). Therefore, the credibility of the decision outcomes determined by MCDA methods can be affected by the embedded uncertainty if not stated explicitly or dealt with in the model. The focus of this research is on a specific type of internal uncertainty, judgement uncertainty. This issue is generally not addressed in urban water decision problems (Lai *et al.*, 2008). Judgement uncertainty is a type of internal uncertainty that deals with imprecision in the assessment of criteria scores for different alternatives and criteria weights. This situation could arise because the external environment provides insufficient information and this forces the DMs to make imprecise judgements.

1.2.3 Preferential dependency

The most common approach adopted in urban water is to use simple additive weighting (SAW) techniques to represent DM's preference structures. A major assumption in this approach is preferential independency (Fishburn and Keeney, 1975). The assumption implies that the preference order between a pair of criteria is independent of any changes made to the preference order of other criteria. It is recognised that assuming the preference of a criterion is independent of another criterion and/or an alternative does not always hold (Fishburn and Keeney, 1975; Saaty, 1996).

1.2.4 Range sensitivity

A common assumption is that DMs assign criteria weights independent of the criteria measuring range (Pomerol and Barba-Romero, 2000; Belton and Stewart, 2005). A number of behavioural studies suggest that the criteria range influence the assignment of criteria weights and this issue is referred to as *range sensitivity* (Goldstein, 1990; Fischer, 1995). A review of the existing water strategies showed that the majority of the DMs in current practice in urban water management do not take in account range sensitivity, in which the evaluation of the relative importance of the criteria are often made independent of the criteria range.

1.3 Aims and objectives

The key aim of this thesis is to develop a decision support approach for evaluating different water strategies. A particular focus is to solve the four identified shortcomings associated with the use of MCDA in urban water management, thereby improving the integrity of the analysed decision outputs. The aims of this thesis are listed in Table 1.1.

Table 1.1 Thesis aims

No.	Aims	Section in thesis	
		Problems identified	Problem addressed
1	Avoid double counting for urban water decision problems	Section 2.5.2 p.46; Section 2.6.1 p.58;	Section 3.4.4 p.100
2	To account for uncertainty associated with subjective judgements in urban water decision problems	Section 2.5.3 p.48; Section 2.6.2 p.63	Section 4.3.2 p.153; Section 5.3.2 p.201
3	To account for criteria interaction in urban water decision problems	Section 2.5.4 p.54; Section 2.6.3 p.66	Section 4.3.3 p.166; Section 5.3.2 p.201
4	Avoid range sensitivity in criteria preference elicitation	Section 2.5.5 p.55 Section 2.6.4 p.68	Section 4.2 p.122

1.4 Research scope

In Australia, the need for better and more efficient management of water in urban environments was spurred by the Intergovernmental Agreement for a National Water Initiative (2004). In response to the initiative, the peak body of the Australian urban water industry, Water Services Association of Australia (WSAA) developed a flexible framework to evaluate the sustainability of various water strategies that incorporates stakeholder engagement (Lundie *et al.*, 2008a). The framework suggests the use of a discussion-analyse-discuss iterative approach to encourage DMs to develop new ideas and allows room for DMs to adjust their scoring. The WSAA framework consists of six phases. The six phases are illustrated in Figure 1.1 and summarised briefly in Table 1.2.

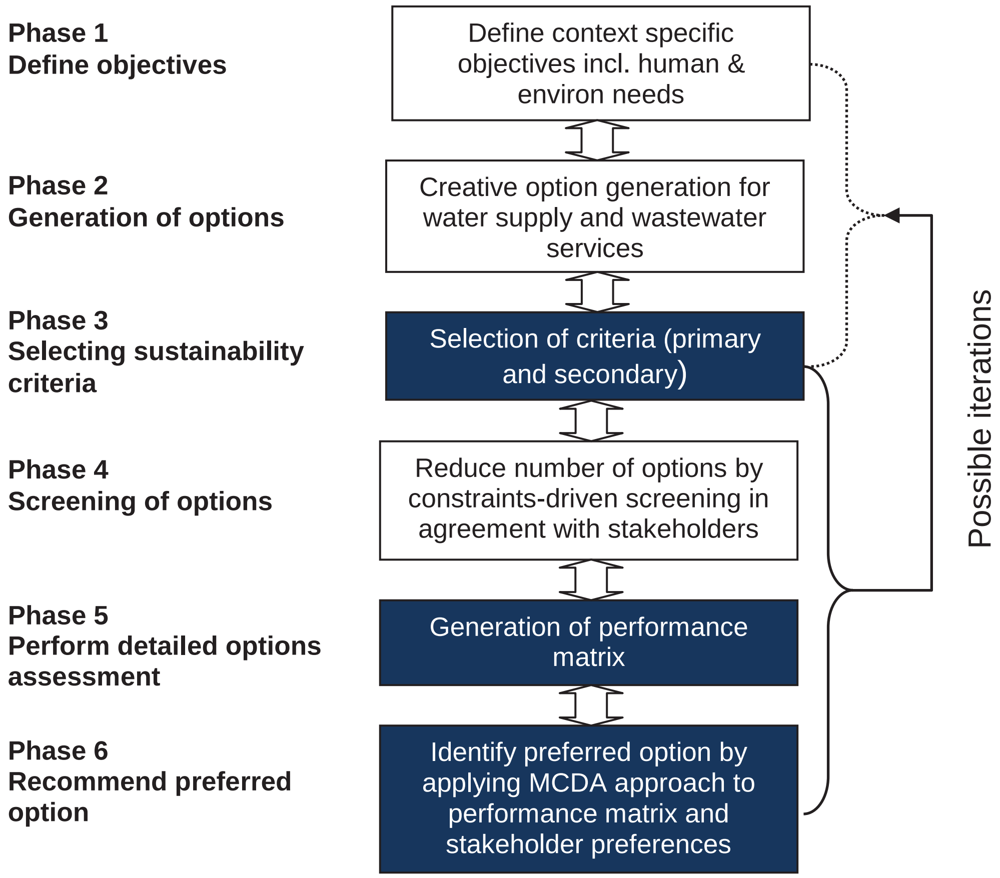


Figure 1.1 WSAA sustainability assessment framework (Lundie *et al.*, 2008a)

The work presented here broadly aligns with the purpose of the WSAA framework in pursuit of more sustainable urban water systems but with a more refined aim of focusing on the methodological shortcomings. The targeted methodological issues can be related to phases of the WSAA framework:

- **Phase 3 (selection of criteria)** – the issue of double counting is addressed in this phase by structuring the criteria in a systematic manner
- **Phase 5 (generation of performance matrix)** – the issues of uncertainty and criteria interaction are addressed by defining the performance matrix differently
- **Phase 6 (recommend preferred option)** – the performance matrix is aggregated to recommend a preferred option under the scenarios that considered uncertainty and/or criteria interaction.

Table 1.2 Description of the six phases in the WSAA framework (Lundie *et al.*, 2008a)

Phase	Details
1. Define objectives	A problem well defined is a problem half solved. This phase is to give details to problem framing which include defining the objectives of the decision making problem and identify key stakeholders.
2. Generation of options	A list of preliminary options is developed in this phase through brainstorming sessions by the stakeholders. These options will be further investigated in Phase 4 for screening, and in Phases 5 and 6 for detail analysis.
3. Selection of sustainability criteria	Sustainability criteria are selected for screening options in the next phase and for prioritising the screened options in detail (Phase 5). The selection of criteria is critical; they should cover the five sustainability categories (economic, human health, environment, technical and social) and encapsulate the various context-specific objectives identified in Phase 1.
4. Screening of options	The purpose of this phase is to reduce the list of options to a feasible number that allows for thorough assessment. The iteration allows any less favourable option screen to be reassessed and improved by mitigation.
5. Perform detailed options assessment	A detailed assessment is carried out for each short-listed option to assess the criteria performance values.
6. Recommend preferred option	The performances of each option are compared using an appropriate multi-criteria methodology for prioritising the options with respect to the sustainability criteria. A final recommendation is made for the preferred option(s) in this phase.

The relevant phases are highlighted in Figure 1.1. Other phases are not within the scope of this thesis, and include:

- Phase 1 (defining objectives and identify key stakeholders)
- Phase 2 (generation of options)
- Phase 4 (reduce options).

The issues related to Phase 1, 2 and 4 rely are not part of the methodological shortcomings identified. Phase 3, 5 and 6 can be generally described as the ‘hard’ component of the framework which deals with the actual decision model. Phase 1, 2 and 4 represent the ‘soft’ component of the framework that prepares the decision problem for modelling. The purpose of Phase 1, 2 and 4 is to structure and refine the decision problems for developing the subsequent decision model. This area is generally well covered with many problem structuring methods available to aid in this regard (Keeney, 1996; Rosenhead, 1996; Eden and Ackermann, 1998; Belton, 1999; Friend and Hickling, 2005; Montibeller and Belton, 2006).

Despite the advancement of having a decision support framework to enhance the way sustainability is incorporated into the decision making process, there are still significant gaps inhibiting their successful implementation (Sharda *et al.*, 1988; Sainfort *et al.*, 1990; Newman *et al.*, 2000; Mysiak *et al.*, 2005). These gaps range from methodological issues of the adopted decision support model to higher institutional factors influencing the support of these tools. The four methodological shortcomings identified in this thesis do not represent all barriers to successful implementation of decision support frameworks. Institutional factors such as values, knowledge frameworks and organisation structures all play a role in affecting the successful implementation of decision support frameworks (Stenekes *et al.*, 2006; Livingston, 2008). Other success or critical factors are: early involvement of end users, a logical decision model, transparency in the decision model, intuitive user interface, and overall user satisfaction with the approach (Poon and Wagner, 2001).

This thesis addressed four identified shortcomings associated with the decision model (Phases 3, 5 and 6) but did not examine these other factors influencing the successful implementation of the developed decision support framework such as the 'soft' component of the decision framework (Phases 1, 2 and 4) which involved institutional and transparency issues .

1.5 Approach

The approach was to develop a decision framework that addresses the four identified shortcomings. The proposed decision support approach is comprised of three stages: (1) problem structuring, (2) preference elicitation and modelling, and (3) aggregation. This structure is in line with most common multi-criteria decision model (Resource Assessment Commission, 1992; Guitouni and Martel, 1998; Belton and Stewart, 2005).

- **Stage 1 Problem Structuring –** the purpose of this stage is to assist in structuring problems rather than directly solving them (Rosenhead, 1996). These types of methods can be broadly described as Problem Structuring Methods (PSMs). Some characteristics of PSMs are that they can accommodate multiple perspectives, function through interaction and iteration and generate ownership of the problem. As discussed earlier in the research scope, this research is restricted to the selection and structuring of criteria (Phase 3 of WSAA framework) (see Chapter 3 in this thesis).

- **Stage 2 Preference elicitation and modelling –** this stage is concerned with constructing a decision model to represent DMs' preferences. There are two components in this stage, which are (1) preference elicitation and (2) preference modelling. The first component is about eliciting the relative importance and perceived performance level for each criterion. The second component is about modelling the relative criteria importance and performance level. This is where the other two shortcomings, judgement uncertainty and criteria interaction are partially addressed. This can be related to Phase 5 of WSAA's framework (see Chapter 4).
- **Stage 3 Aggregation –** this stage is to aggregate preferences across all criteria, with the intention of associating a number or a *global value* with each alternative. The global value allows different alternatives to be evaluated with respect to all criteria. This can be related to Phase 6 of WSAA's framework (see Chapter 5).

To investigate the effectiveness of addressing internal uncertainty and criteria interaction, four cases with different assumptions were devised that span across the last two stages (stage 2 and stage 3):

- Case 1: Without judgement uncertainty and criteria interaction
- Case 2: With judgement uncertainty
- Case 3: With criteria interaction
- Case 4: With judgement uncertainty and criteria interaction.

With respect to different cases and the associated assumptions, the method adopted in stage 2 and stage 3 were different for each of the four cases. The criteria selected in stage 1 remained the same throughout stage 2 and stage 3.

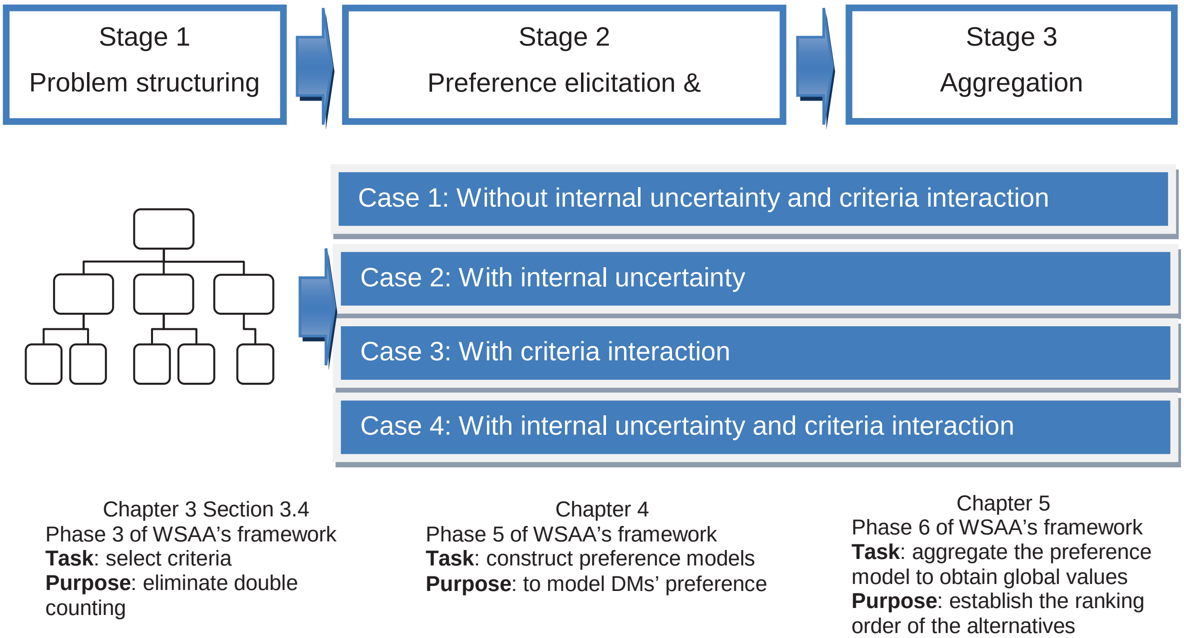


Figure 1.2 Proposed decision framework and approach

Under stage 3 aggregation, the global values from cases 2, 3 and 4 were compared to the first case to investigate the influence of internal uncertainty and criteria interaction. This framework was applied to an urban water decision making case study, the Gold Coast Waterfuture (GCWF) strategy.

1.6 Contribution of the study

This thesis contributes to the field of decision aid for sustainable urban water management in the following ways:

- An improved decision support approach that enables an understanding of various factors that affect the decision models, including double counting, judgement uncertainty and criteria interaction
- Extends the current theories of managing the four identified shortcomings, and provides new and practical procedures for addressing them.

This research is significant because the application of MCDA processes in Australia's natural resources management is largely limited to cost-benefit analysis, with the benefits typically measured using a weighted multi-criteria function (Hajkowicz, 2009). This may be due to the fact that the majority of the MCDA research work is in the European countries and the United States (Roy and Vanderpooten, 1995; Figueira *et al.*, 2005). Most of the MCDA applications in the field of urban water management in

Australia do not consider the issues with double counting, judgement uncertainty, criteria interaction and range sensitivity. For a more detail review of the use of MCDA in urban water management, refer to Section 2.5 p.38.

1.7 Thesis structure

Chapter 2 reviews the literature and background knowledge upon which this research draws. The paradigms in urban water systems development are firstly reviewed. This is followed by a review of the common integrated approaches for urban water sustainability assessment, with a particular focus on MCDA, highlighting four generic shortcomings with its applications.

Chapter 3 draws from the four shortcomings identified in Chapter 2 and presents the outline of a new decision support approach to address these shortcomings. The materials and methods adopted in this research to test-proof the framework are presented. This chapter also illustrates the first stage of the framework (problem structuring) using a case study, the Gold Coast Waterfuture strategy.

Chapter 4 presents the second stage of the framework (preference elicitation and modelling). A new preference elicitation technique that overcomes the issue of range sensitivity is presented. This is followed by the presentation of the four cases which assumed different types of preference models to describe the problems of judgement uncertainty and criteria interaction.

Chapter 5 presents the third stage of the framework (aggregation). It reports on the aggregated results from the four preference models and provides a sensitive analysis to highlight the reliability of this approach.

Chapter 6 summarises the decision support approach. A reflective summary of this research is provided, addressing the research significance, achievement of the thesis aim and limitation of the study.

2 Literature Review

2.1 Introduction

The previous chapter highlighted the challenges in making sustainable urban water decision making. The challenges are associated with the integration of sustainability assessment into the current practice of urban water decision making. A flexible integrative framework for evaluating long-term water strategies is therefore required to guide decision making through the complex problem of balancing social, environmental and economic aspects. This chapter reviews literature associated with integrated sustainability assessments in urban water management to establish the existing short-comings related to the current practice and identify the gaps filled by this thesis.

This chapter begins by looking at the development of early urban water systems since the beginning of the industrial revolution (Section 2.2). The development lead to what is known as today's urban water systems with large pipes and dams. Alongside with the infrastructure expansion is a shift in the philosophy behind urban water management. The shift from a service-orientated approach to increasing awareness of sustainability is documented in Section 2.3. Four commonly used approaches to integrate sustainability in urban water decision making are examined in Section 2.3.4. The use of the multi-criteria decision aid (MCDA) has emerged as a key approach in the water industry as the number of published MCDA studies has increased dramatically over the last two decades (Hajkowicz and Collins, 2007). Here MCDA is reviewed in Section 2.4 in the context of urban water management used in a decision making framework. Shortcomings associated with MCDA are identified in Section 2.5 to establish the gaps affecting the integrity of MCDA applications in urban water management. The rationale for the selection of tools to solve the shortcomings is provided in Section 2.6. The structure of this chapter is illustrated in Figure 2.1.

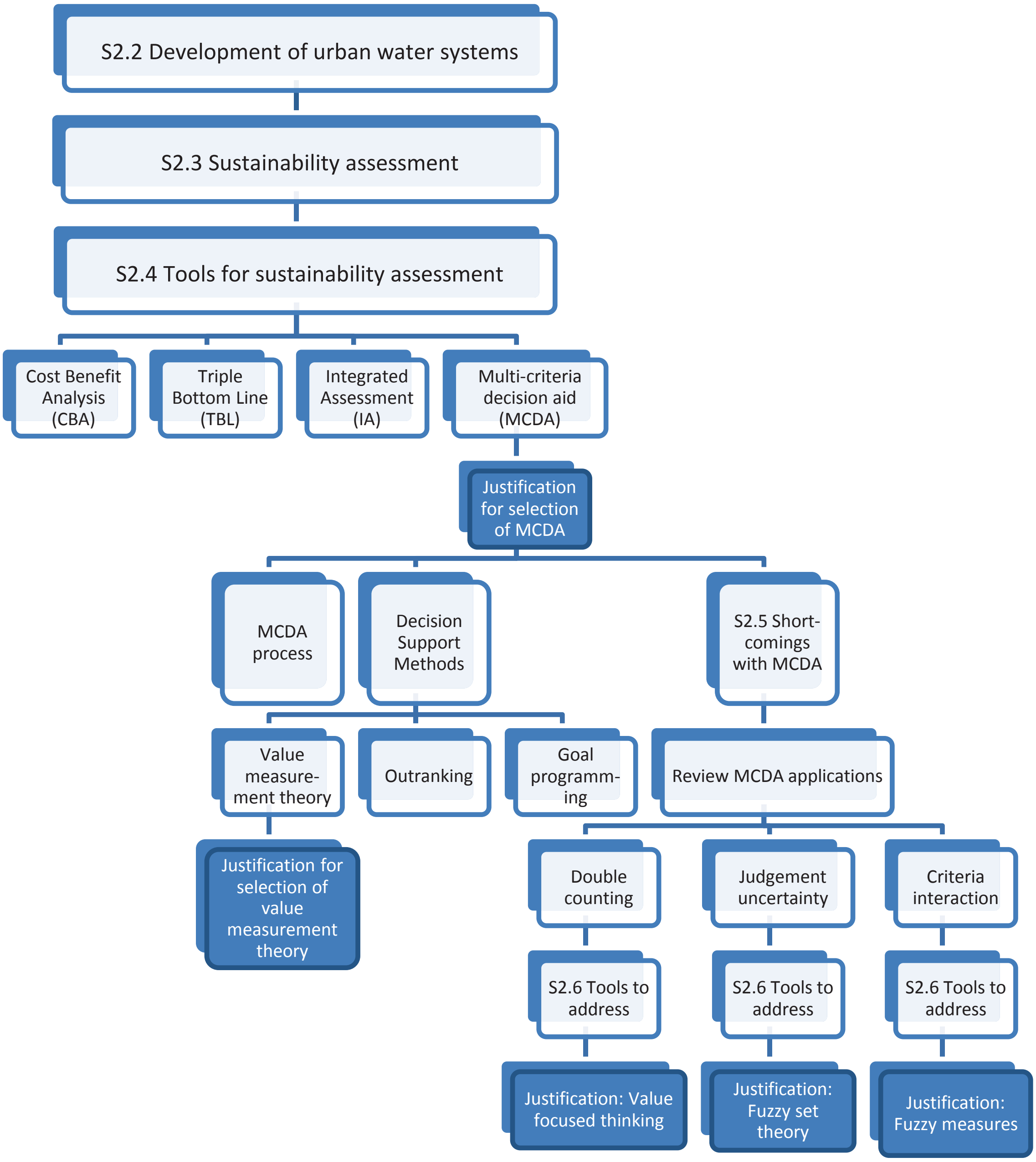


Figure 2.1 Structure of Chapter 2 Literature Review

2.2 Development of urban water systems

2.2.1 Pre-industrial

In the early history of urban city development prior to industrialisation in the 19th century, water provision and sanitation services was predominately managed in a localised manner (Melosi, 2000). Water was primarily sourced from surface rivers and local wells. Likewise, sanitation was managed on an individual basis by having household toilets using privy vaults (bucket systems emptied periodically by individuals) or leaching cesspools (holes in the ground). The disposal of human waste and household wastewater often found their way to surface drainage on the streets and became open sewers from overflowing cesspools and privy vaults. It was common for city dwellers in the early urban settlements in both Europe and America to use the streets as dumping ground for their wastes. The condition of cities was poor and cleanliness of the streets was largely neglected.

Epidemic diseases such as cholera, typhoid, typhus and tuberculosis were prevalent, but the causes were largely unknown at that time as it was common to associate diseases with spiritual punishment or the 'wrath of God'. There were also different camps of beliefs that the diseases were either a result of foul air (miasma) or transferred via infection (germ theory) (Harreomoës, 1999). With the causes remaining unknown until the late 1880s (Ashbolt *et al.*, 2001), expansion of cities continuing and driven largely by industrialisation, the condition of the cities became an increasing threat to public health.

2.2.2 Industrial

Compounding the problem was the pollution of open water sources by contaminants from privy vaults, cesspools and street drainage. In response to this, centralised municipal water supply systems emerged to deliver water via pipes to users, but with only limited distribution pipe works servicing mostly affluent neighbourhoods and private businesses. This change had brought some improvement to public health and also provided a new mechanism for fire protection. The fear of fire was also a major motivator for the centralised water supply system in densely populated areas where the housing structures were largely made from wood. But despite the effort to improve public health, epidemic outbreaks of cholera were still prevalent because the management of wastewater remained largely ineffective.

In the mid-19th century the notion that the poor sanitation environment was linked to the well-being of individuals was popularised by Edwin Chadwick, a leading pioneer sanitarian (Lewis, 1970). His idea of advancing the cleanliness of the cities was to improve the conditions of the public works including waterworks, sewers, paved streets and ventilated buildings. He proposed a 'hydraulic sewer system' that would bring potable water into the households and then contained via water-closets. The nutrient rich wastewater would be carried away via sewer lines and deposited into agricultural fields as manure. The recycling of sewage as agricultural fertilizer, however, was not implemented but instead the wastewater was directed into rivers and streams.

It was not until in 1854 when John Snow, a London physician, proved water as a transmitting agent during a cholera epidemic in London (Vinten-Johansen, 2003). This perspective was further widened in the late 19th century to accept that a specific organism was linked to a specific disease, thus establishing the germ theory. This change of understanding had placed greater emphasis on the environment as a major factor in the improvement of public health. This shift of focus had also reshaped the role of water to become an important agent for the transport of wastewater out of the cities.

The development of centralised water supply systems gradually gathered momentum in the mid-19th century in America (Burian *et al.*, 2000). The era of private water services began to phase out as public ownership of major waterworks began to increase. The shift towards a centralised management system in the authority of a city government was not only motivated by the protection of public health but also the need to supply an adequate amount of water to secure economic growth.

2.2.3 Twentieth century

The success of this development has led to what is today's urban water systems, which include collection, treatment and distribution of water, wastewater and stormwater (Larsen and Gujer, 1997). The concept of 'big pipe' or a highly centralised management approach to urban water systems was firmly established as the pathway to growth for all cities around the world (Drangert *et al.*, 2002). The water supply systems source water from increasingly larger distances, and infrastructures expand dramatically with larger water reservoirs and pipelines for inter-basin transfers.

The driving forces behind the expansion in the twentieth century water resource systems evolved from fire fighting and public health protection to meeting demand from increasing population growth, industrial development and expansion of irrigated agriculture (Gleick, 2000). As per capita water demand, agricultural production and level of economic productivity were always projected to rise, the management approach adopted was to continue expanding the systems to meet the need. The water planning becomes supply driven and the solution to the bridge the gap by providing more physical infrastructure assumes water supply is a limitless resource.

Despite the success of the big pipe approach to manage water supply, there were new challenges found in inequitable and inefficient distribution of water resources, and increasing vulnerability to excessive demands. A parallel problem was the dramatic modification of the natural environment and hydrological cycles, in particular by the widespread development of dams. As a wide range of environmental problems became more publicised, public acceptance of major water projects also lessened (McGully, 1996). Accompanying this was the realisation of other environmental problems such as the use of pesticides, deforestation, the pollution of waterways and loss of biodiversity.

This environmental movement gained momentum in the 1960s and 1970s, as it became a popular concept to challenge the traditional process of economic growth. The spirit of environmentalism was best captured by some of the influential publications such as Rachel Carson's *Silent Spring* (1962) and Schumacher's *Small is beautiful* (1973). This environmental movement had results in delaying or halting several major water projects due to opposition from the public such as the Welcome Reef Dam in Australia (Seebohm, 2000). The conventional water planning approach faced constraints not only by environmental limits, but also social and economic limits. The cost of new water supply systems and the maintenance cost were increasingly more expensive and also more difficult to justify taking into account environment and social factors which were traditionally treated as external costs.

2.2.4 Sustainability awareness in the twenty-first century

The constraints in environmental, socio-economic factors challenged the way traditional water planners thought about managing water resources, shifting their focus from large-scale physical solutions to explore improvement in managing demand or seeking alternative supplies. The underlying concerns acknowledge that economic development and environmental protection and social harmony can operate simultaneously. This forms the basis of sustainability awareness which is a common concept recognised by world leaders (Adams, 2006). In recognition of sustainable development, one of the United Nation's Millennium Development Goals is to halve by 2015, the proportion of people without sustainable access to safe drinking water.

The concept of sustainability has continuously become more multi-disciplinary including not only social, environment and economic factors, but also other factors such as institutional, governance, health and technological issues. All of these factors played important roles in bringing about a change in the management view for a more decentralised approach, although there is still large resistance and reliance on physical infrastructure (Livingston, 2008). The awareness of sustainability is re-shaping the development of our urban water system in the twenty-first century (Water Services Association of Australia, 2009). Recently, there is strong focus on water conservation which can be provided through alternative supplies such as recycled water and rainwater tanks. This is made possible through new milestones achieved in membrane technology (Fane and Leslie, 2004) as demonstrated by the Singapore Newater project (Seah *et al.*, 2003) and Orange County California's indirect portable reuse project (Leslie *et al.*, 2000). Alongside with water conservation is the new paradigm on demand management which focuses on managing urban water through a mixture of restriction, pricing and water efficient strategies (Turner *et al.*, 2008). Costing analysis has a dominated role in the planning of water demand management (Mitchell *et al.*, 2007), together with end-use modelling (White and Fane, 2002). The development of the sustainability concept is examined more closely in the following to understand the influence of it on urban water management decision making.

2.3 Sustainability

2.3.1 The concept of sustainability

The need to incorporate sustainability in all development activities was first recognised in the 1972 Stockholm Conference introduced by the International Union for the Conservation of Nature (IUCN). The well-known three pillars for sustainability, economy, environment and society were also established formally in the World Conservation Strategy published by IUCN in 1980 (Adams, 2001). These principles were further promoted through international consensus in 1987 by the World Commission on Environment and Development (WCED) Brundtland Commission's report *Our Common Future* (WCED, 1987). The Brundtland report defined sustainable development as 'the need to meet the present requirement without compromising the ability of future generation to meet their own needs.' The principles were further established in the 1992 Rio summit conducted by the United Nations Conference and again at the World Summits on Sustainable Development in 2002 and 2005.

The concept of sustainability was extended to urban water management as dictated in *Agenda 21*, with a clearly defined objective (United Nations, 1992, s. 18.2). Lundin (1999) described 'a sustainable urban water system should over a long time perspective provide required services while protecting human health and the environment, with a minimum of scarce resources'. Another definition offered by the American Society of Civil Engineers (ASCE) and United Nations Educational, Scientific and Cultural Organization (UNESCO) (1998) is 'sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity'.

2.3.2 Sustainability assessment

The concept of sustainability requires that the management of water resources should be viewed holistically (Giupponi *et al*., 2006). The traditional management approach that builds on advancing technological capacities is no longer sufficient to meet the demand as evident through the challenges described above and the value of the approach is being questioned (Adams, 2006). The need to integrate socioeconomic and environmental factors into the decision making process is clearly raised in the prominent *Agenda 21* signed at the 1992 Earth Summit in Rio de Janeiro. The new paradigm in water management takes the view that the process of decision making requires restructuring to ensure socioeconomic and environmental issues are fully integrated as well as incorporating a broader range of stakeholder participation (United Nations, 1992).

This recognition has led to the development of Australian urban water sustainable frameworks such as WSAA's sustainability framework (Lundie *et al.*, 2008a), Water Research Foundation's Integrated Urban Water Management (IUWM) manual (Maheepala *et al.*, 2010), and WSAA's guide to demand management (Turner *et al.*, 2008) which are beginning to be used by the industry. Outside of Australia, there are also a number of decision support frameworks developed in different parts of the world such as the European's Water Directive Framework (Giupponi, 2007), United Kingdom's Sustainable Water-industry Asset Resource Decisions (SWARD) (Ashley *et al.*, 2004), and Swedish's Urban Water Programme (UWP) (Hellström *et al.*, 2000). Although it still remains a challenge to link the investment activity (e.g. sustainability assessment) to the outcome (e.g. more sustainable urban water system) (Hajkowicz, 2009), the concept of sustainability is rooted in most urban water system management.

There are many different approaches to perform sustainability assessments (OECD, 2008). It has been long recognised that there is an absence of a truly integrated sustainability assessment (Buselich, 2002). The task of conducting sustainability assessment becomes difficult because the definition is vague and contains multiple dimensions. There are various definitions given to sustainability and it is expected to evolve over time as new knowledge is gained (WCED, 1987; Costanza *et al.*, 1991; Pearce and Atkinson, 1993; Costanza and Patten, 1995; Schubert and Láng, 2005). Munda (2005) noted the common quantitative approach to 'measure sustainability' has many limitations, both theoretically and practically due to the complexity and inherent fuzziness in the concept. The following describe the general common components of sustainability assessments, and introduce four typical approaches in the field of urban water management.

2.3.3 Sustainability criteria structure

The water industry has played a key role in advancing the science of integrated sustainability assessment, particularly in the development of sustainability criteria and indicators. The use of criteria makes the concept of sustainability more operational and practical. Sustainability criteria are the set of factors that can be used to assess a range of options, for their contribution to achieving sustainability objectives (Foxon *et al.*, 2002). There are different approaches to structure the hierarchy of sustainability criteria in different frameworks. In decision science, such a hierarchy of criteria is known as a *value tree*, which is a structured way of presenting the DM's value in a tree-like format. The different approaches to value tree structure offered by the frameworks can be grouped into two main camps of approach: sustainability approach and pressure-state-response approach.

Sustainability approach

The sustainability approach is based on the three pillars of sustainability: environmental, social and economic. DMs can generate criteria under each of the pillars to form a criteria tree. The UK-based research project SWARD developed a guide for water service providers to make decisions. They defined the hierarchy with four main categories: economic, environmental, social and technical (Ashley *et al.*, 2004). These categories capture the three main principles of sustainability together with an additional technical criterion, specifically related to the performance of urban water systems.

The Swedish UWP identified a set of five sustainability categories: health and hygiene, social and cultural, environmental, economic, and technical and functional aspects (Hellström *et al.*, 2000; Malmqvist *et al.*, 2006). The same categorisation also applies to WSAA's framework (Lundie *et al.*, 2008a). These five categories are parallel to the four categories defined by SWARD. These five categories expand into more detailed criteria. Different frameworks offered different lists of criteria depending on the decision context. It is worth noting that there are other lists of criteria for assessing urban water or natural resources sustainability that can be found in Loucks and Gladwell (1998), Lundin (1999), American Society of Civil Engineers (ASCE) and United Nations Educational, Scientific and Cultural Organization (UNESCO) (ASCE and UNESCO, 1998), Spangenberg and Bonniot (1998), Hellström *et al.* (2000) and Balkema (2002).

Pressure-State-Response approach

The Pressure-State-Response model is a framework based on the concept of causality between human activities (pressure), the consequences exerted on the environment (state), and the society's responses (response). The framework presents environmental information in terms of the indicators of the 'pressure', 'state', and 'response' (OECD, 1993). The European Water Directive Framework adopts a Driving force-Pressure-State-Impact-Response categorisation which is an extended version of the Pressure-State-Response model (Giupponi, 2007). This model aims to capture the cause-effect relationships between the human and environment system holistically. It allows the causal relationships to be traced by linking the effects of a driving force (e.g. discharge of raw sewage) to a certain pressure (e.g. increase nutrients in waterways) to a change in the state of the resource (e.g. water quality deterioration) to an impact (e.g. algae bloom) to possible response (e.g. build treatment facility). Criteria are selected from the framed pressure-state-response model.

There are pros and cons with each of the two approaches. The advantage of the sustainability approach is that the three pillars of sustainability provide a general scope for DMs to brainstorm. The three pillars can be extended into four (the SWARD frameworks) or into five (the UWP and the WSAA frameworks) categories. This can be a potential issue because the selection of criteria is limited by the number of adopted sustainability categories.

The advantage of the pressure-state-response approach is that DMs can explore the complex linkages between human activities and the consequences on the state of the environment. On the down side, the identification of criteria is not as straightforward as it is for the sustainability approach. The criteria are embedded within the complex relationships and DMs need to carefully identify the parameters that constitute their system of value. In light of this, this thesis adopted the sustainability approach because of the clarity it offered and also its ability to reflect closely DMs' value systems. The adopted sustainability criteria structure and the associated terminologies are defined as follows:

- *Principles* – the normative definitions or goals for sustainability (Foxon *et al.*, 2002). The term *principle* has the same meaning as an *objective* which is a statement describing the desire state of reality or the direction that a DM choose to follow for a certain attribute (Zeleny, 1982; Lu *et al.*, 2007).
- *Categories* – the grouping that represents the different aspects of sustainability.

- *Primary criteria* – they have the same meaning as *attributes* in MCDA terms which are parameters that represent any aspect of a given problem assumed by the DM. These parameters can be used to make a judgement about the relative sustainability of a set of options (Zeleny, 1982).
- *Secondary criteria* – they are parameters that express more accurately the preferences of the DM on given primary criteria (attributes).
- *Indicators* – measure the past and current values of specific criteria which can be used to benchmark future performances.

The principles represent the desired direction that the DMs want to follow with respect to sustainability. The principles of sustainability are formally defined in the Brundtland report (WCED, 1987). One or more categories can be associated with each principle. The next level down is a small number of primary criteria which would cascade down to a larger number of more specific secondary criteria. The bottom level is a list of indicators for assessing the performance values of the urban water systems (Figure 2.2).

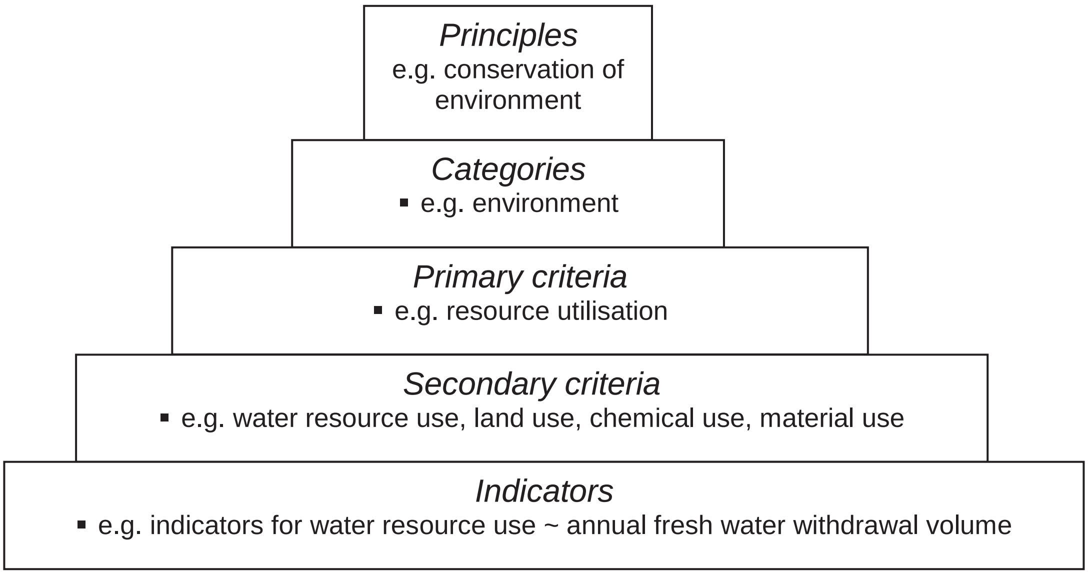


Figure 2.2 Hierarchy of sustainability criteria

2.3.4 Tools for sustainability assessment

A range of assessment tools are available for generating performance details for the sustainability criteria and indicators. The purpose of the assessment tools are to present information in a synthesised and logical manner to the DMs, to assist in their decision making. It is important at this point to give a formal definition of decision making to see how sound decision making can contribute to the success of achieving sustainable urban water systems. Simon (1959) described decision making as '*the process of choice that leads to action*'. Decision making is in general a very complex issue because it involves a large number of stakeholders with conflicting views. Adding to the degree of complexity is the issue that the problems of urban water systems are become increasingly interdisciplinary. The conventional approach to decision making related to urban water management generally considers the three (social, economic and environmental) aspects of sustainability separately. Understanding how sustainable a water system is requires holistic thinking. In order to deal with the multi-dimensional complexity of urban water system, being guided through the complex process of choice requires a set of tools such as integrated sustainability assessments to provide relevant information. Integrated sustainability assessment offers a forum for integrating the different elements of sustainability for exploring new pathways to sustainability. It is formally defined as:

> a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development (Jäger et al., 2008).

Some of the popular assessment tools applied in water resources management include: Cost-benefit Analysis (CBA), Ecological Footprint (EF), Environmental Impact Statement (EIS), Environmental Risk Assessment (ERA) including chemical and microbial risk assessment, Integrated Resources Planning (IRP), Integrated Assessment (IA), Integrated Urban Water Management (IUWM), Life-cycle Assessment (LCA), Life-cycle Costing (LCC), Least-Cost Planning (LCP), Material Flow Accounting (MFA), Multi-criteria Decision Aid (MCDA), Social Impact Assessment (SIA) and Triple Bottom Line (TBL).

However, based on the definition of integrative sustainability assessment given above, not all of these tools are qualified to become an integrative tool. Some of these tools do not have the mechanism to integrate multiple measures into a single assessment (e.g. EIS, EF, ERA LCP, LCA, LCC, SIA). For example, EF and LCA are frequently employed to inform decisions makers of the potential environmental impacts associated with an action (Peters *et al.*, 2006; Peters *et al.*, 2008). Therefore, they are limited to being assessment tools to assess the performance for the sustainability criteria or indicators. Other tools such as IRP and IUWM, act as over-arching planning frameworks. In particular, IRP is a comprehensive framework to help structure the decision problem through supply and demand balance planning, and is useful as an option screening tool (McFarlane *et al.*, 2005; White *et al.*, 2006). Therefore, they are not considered as a mechanism for integration. The tools that have the integrative mechanism are: CBA, TBL, IA and MCDA. It is recognised that there are other integrative approaches that exist but the commonly used ones in urban water management are discussed here. These four commonly used integrative approaches in urban water management are reviewed in the following section. A summary comparing the four integrative approaches is presented in Table 2.1.

Cost-benefit analysis

CBA is one of the simplest forms of integration approach covering environmental and socio-economic concerns. Any environmental impact that affects valued commodities together with the benefits are considered as externalities. These externalities are converted into monetary terms and comparison is made on relative costs/benefits. There are a number of techniques to convert externalities into monetary values, including change-in-productivity, loss of earnings, defensive expenditures, travel cost, wage differences, property values, avoidance cost, replacement cost, and the contingent valuation method (Lutz and Munasinghe, 1994). CBA also involves discounting these monetary values over the life time of the system into present values based on some predetermined discount rate to reflect the way humans value their goods (Pearce *et al.*, 2006).

CBA has proven to be useful because of the one single aggregated result obtained which helps to clarify and provide information about the costs and benefits of alternatives (Thampapillai, 1991). CBA has been widely adopted in water engineering applications traditionally because of its simple monetising approach (Pearce *et al.*, 2006). To a certain degree of truth, mapping out costs and benefits is a fundamental step towards better understanding of the decision-making problem. The key issues remaining however are the methodological shortcomings associated with quantifying the costs and benefits and how to interpret the implications of the results. As a consequence, CBA has received considerable criticism because of the high level of ambiguity and uncertainty in translating value judgement into numerical values (Costa and Vansnick, 1997; Burritt, 2004). Also, some of these impacts cannot be priced according to market values and are recorded as intangible externalities (Hanley and Spash, 1993). In the absence of a market, pricing an environmental impact or benefit can be subjective. Value judgement is the primary method to allocate these monetary values and they are susceptible to biased judgement. Selection of the discount rate and the effects it has on values in distant future are also some of the major controversies concerning CBA. As the value of the discount rate increase the time effect also increases and diminishes the value of goods in the future (Hanley and Spash, 1993). As such, Arrow *et al.* (1997) suggested that CBA has a potential role to play to promote better understanding, but it should not be the sole basis for making decision in policy regulation.

Triple bottom line

The concept of TBL first emerged in 1994 and flourished since the late 1990s among water service providers (Elkington, 1998). TBL involves data collection, analysis and presentation of information related to the economic, environmental and social aspects of an organisation. It extends corporate social responsibility from the concept of sustainability, motivating organisations to address sustainability issues in a more integrated way. It is itself not only a reporting tool, but also a concept for guiding selection of indicators for measuring performances. The benefit of TBL is in expanding the users' view by incorporating social elements into their thinking. In the process of measuring social and other non-financial performances, interactive dialogue takes place between the company and stakeholders which goes beyond the traditional engineering assessment (Suggett and Goodsir, 2002).

TBL reporting is increasingly popular with water service providers in Australia not just as a tool to report social performance in conjunction with environmental and economic performances, but also as a planning framework for sustainability assessment (Christen *et al.*, 2006; Coffman and Umemoto, 2010). However, the level of sophistication as a tool is not high. It lacks a robust model for integrating the financial, social and environmental information.

Integrated assessment

IA is an emerging discipline with emphasis on the process to bring together a broad set of disciplines characteristic of the decision problem through scenario management and stakeholder engagement (Rotmans and Asselt, 1996; Rothman and Robinson, 1997; Parker *et al.*, 2002; Jakeman and Letcher, 2003). It has its root from the U.S. Global Change Research Program (CIESIN, 2005), but as an intuitively based process it is not new (Rotmans and Asselt, 1996). IA has many definitions, but despite its diversity; IA can be described as "*a structured process of dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders, such that integrated insights are made available to decision makers*" (Rotmans, 1998).

IA is increasingly being applied to integrated management of catchments and water resource allocation problems (Kolhoff *et al.*, 1998; Jakeman and Letcher, 2003; Letcher *et al.*, 2004; Croke *et al.*, 2007). Some of the integrative approaches adopted by IA are system dynamics, Bayesian networks, agent-based model and expert systems. The technique operates on a variety of levels, scales and thus, diverse methods can be used and not limited to technical modelling (Rotmans and Asselt, 1996). Brouwer *et al.* (2003) provided a comprehensive review of the IA concept and methods for water and wetland management. However, IA is still a very new structured discipline. As a relatively, IA is still mostly qualitative in nature without a robust model to integrate the overlapping research areas of technical assessment, policy analysis and risk analysis.

Multi-criteria decision aid

As a decision analysis tool, MDCA is a structured approach for supporting decision making when dealing with more than a single criterion and allows relative importance to be placed upon each criterion by the user (Resource Assessment Commission, 1992). MDCA is used as a support tool to guide decision makers through a process of organisation, establishing values and judgement, analysis and presentation of information, in order to identify a preferred course of action. The aim of MDCA is to make explicit account of multiple and conflicting criteria, in such a way that the DMs are able to learn about the decision problem, about their own and other DMs' opinions.

The economists of the late 19th and early 20th centuries are considered as the pioneers of multi-criteria decision science (Pomerol and Barba-Romero, 2000). Followed by a number of fundamental works in the mid-last century such as von Neumann and Morgenstern's game theory (von Neumann and Morgenstern, 1944) and Arrow's social choice theorem (Arrow, 1951), MCDA gradually acquired its own problem formulation, philosophy and terminologies by the 1960s. The field of MCDA began to expand rapidly in between the 1960s and 1970s, a number of classical methods appeared such as the goal programming (Charnes and Cooper, 1961), utility theory (Keeney and Raiffa, 1976) and outranking method (Roy, 1968).

MCDA is regarded to have considerable value to natural resources managed because evaluating natural resources management problems involve making measurements for a series of criteria (Smith and Theberge, 1987). The application of MCDA in the field of water resources management grew sharply since the mid-90s (Hajkowicz and Collins, 2007). In a recent review of MCDA for water resource planning and management, Hajkowicz and Collins (2007) showed that MCDA is heavily used for water policy evaluation, strategic planning and infrastructure selection.

Recently, stakeholder engagement is becoming an integral part of the MCDA process (Banville *et al.*, 1998). As such, different frameworks that incorporate stakeholder engagement into the MCDA processes are developed. There are a number of well-structured approaches to manage stakeholder involvement in MCDA-supported problem solving activities (Banville *et al.*, 1998; De Marchi *et al.*, 2000; Lawrence *et al.*, 2000; Hämäläinen *et al.*, 2001; Munda, 2004; Messner *et al.*, 2006).

Justification for the selected integrative approach, MCDA

An overview of the strength and weaknesses of the four integrative approaches is shown in Table 2.1. There is no clear definition of the best approach to integrate sustainability because this is highly dependent on the decision problem context, data availability and DMs' preferences. All four of the methods have their strengths and weaknesses, but

MCDA is regarded as having potential value to urban water management, and is therefore selected as the integrative approach for the following reasons.

Support for stakeholder engagement

In the prominent Ǻhrus convention, public participation and access to information is recognised for enhancing the quality and implementation of decision making (UNECE, 1998). Stakeholder engagement is about investigating the motivation for exchanging information and opinions, which is important for constructing meaningful dialogue between stakeholders (Ker Rault and Jeffrey, 2008). The lack of sufficient integration of stakeholder engagement in the decision making process is a bottleneck slowing down the adoption of decision support instruments (Banville *et al.*, 1998).

Examples of past water project failures due to the lack of public consultation have fuelled the emphasis on early public participation. A literature review of the factors influencing the perception of water recycling by Po *et al.* (2004) revealed that the main reason major water recycling projects failed was due to public opposition. Such a case is San Diego's water repurification project that failed to gain public support; as has been the case with many others, raising the need to reconsider the governance of water systems generally (Stenekes *et al.*, 2006). Inclusion of broad stakeholder participation as an integral component in the decision making process related to water management is well accepted (Mostert, 2003; Pahl-Wostl *et al.*, 2007). Therefore, integration of stakeholder engagement to represent different perspectives and interests is a basic requirement in order to develop robust recommendation for any decision problems.

The support of stakeholder engagement in MCDA is two-fold. Firstly, there are many different stakeholder engagement support procedures developed as part of the MCDA process as discussed in Section 0 p.26. Secondly, the distinctive phases within the MCDA process offer transparency for stakeholders to understand and to identify any mistakes made during the process. Although various MCDA methods have different degrees of transparency, Söderberg and Kumar (2004) recommend that a less complex MCDA method can be used as a communication tool for public participation.

The other integrative approach, CBA is limited to being an analytical tool and not a framework for incorporating public participation. The monetisation approach is highly subjective and this can potentially trigger ethical debate surrounding this issue. TBL is useful as a communication tool for reporting but it lacks the rigour for integrating the various components together to generate new information, which is important for enhancing social learning. For IA, in recent years, the introduction of participatory methods has resulted in the development of a more diverse set of tools. However, the issue remains with the need to improve the internal quality, rigour and the consistency of the technical model.

Increase understanding

MCDA provides a structural approach to assist DMs to explore and understand their own values, which is useful as a means of communication between DMs. This is particularly important for reaching consensus when there are conflicting views in collaborative work (Mendoza and Martins, 2006). The opportunity for the DMs to have a dialogue is a crucial factor to any meaningful participation of stakeholder in the decision making process (Ker Rault and Jeffrey, 2008). MCDA provides the platform for facilitating such a dialogue to occur and to empower the DMs' ability to form opinion through social learning.

Explicit trade-off evaluation

MCDA makes trade-offs between different dimensions of the problem explicitly, but each of the other integrative approaches, such as CBA, only allow trade-offs to be made within its sensitivity analysis (Joubert *et al.*, 1997). MCDA offers a platform founded on sound mathematical models for DMs to explore and assess trade-offs between the achievements of alternatives (Mysiak *et al.*, 2005).

Allow mixture of data

MCDA allows different types of data (qualitative and quantitative) to be synthesised into a single value without the assignment of monetary values to all data. Thus, avoiding over-emphasising the economic component of the decision problem which has dominated the conventional water management decision making philosophy (Joubert *et al.*, 1997). MCDA can also assist in implementing the new sustainability paradigm by broadening the DMs' perspective.

Table 2.1 Common features of the four integrative approaches used in integrated sustainability assessment

Method	Philosophy	Strengths	Weaknesses	Stakeholder engagement	Common features
Cost Benefit Analysis (CBA)	Option costs/benefits converted into monetary terms. Relative costs/benefits compared. Values discounted over the life-time of the system into present values to reflect the way humans value their goods.	CBA has proven to be useful because of the one single aggregated result obtained which helps to clarify and provide information about the costs and benefits of alternatives, highlighting the trade-offs.	High level of ambiguity and uncertainty in translating value judgement into monetary values. Some of these impacts cannot be priced according to market values.	CBA is an analytical tool, not a framework for incorporating public participation, but part of the process of conducting CBA, social perception and values may involve public consultation.	Tool for quantifying externalities or intangible matters. Highlights trade-offs. Single cost criterion approach.
Triple Bottom Line (TBL)	Originated as a reporting concept. Evolved as a framework for guiding selection of indicators for measuring performances. Not only a reporting tool, can be used as a decision making framework by incorporating environmental and social factors into decisions.	TBL is widely adopted by water service providers because of its ability to be used as a planning and communication tool. It suffices as a corporate reporting and communication tool.	Lack of academic development and citation. Also lack of integration; indicators for the three pillars are reported separately without any holistic assessment.	Multi-dimensional reporting and communication tool useful as an integrative framework for engaging stakeholders.	Not a precise measuring tool. Multi-dimensional reporting and planning tool. Public participation involvement.
Integrated Assessment (IA)	Structured process of dealing with complex issues, using knowledge from various scientific disciplines and/or stakeholders—integrated insights are presented to DM.	Useful for framing issues and as a communication tool between scientists and DM. Operates on a variety of levels and scales, and thus diverse methods can be used not limited to technical modelling.	Relatively new structured discipline. Still mostly qualitative in nature without a robust model.	As various scientific disciplines and stakeholders are drawn together in the process of IA, the process can become a stakeholder engagement framework.	Interactive, transparent framework. Process enriched by public participation. Linking of research to policy. Iterative, adaptive approach. Recognise missing knowledge.
Multi-Criteria Decision Aid (MCDA)	As a decision analysis tool, MCDA is a structured approach with a set of procedures to follow for aiding decision making when dealing with more than a single criterion.	Provides a structured framework to deal with multi-criteria problems which are often very complex issues.	Requires considerable cognitive effort from DM to make judgements, especially in setting up preference models.	Generally requires a problem structuring method that encompasses the process of stakeholder engagement.	Integrative structured framework. Multiple criterion approach. Variant branches exist. Various approaches to conduct integration.

2.4 Multi-criteria decision aid

The study of multi-criteria analysis in decision making science has led to the development of multi-criteria decision making (MCDM) or multi-criteria decision aid (MCDA) — the latter term emerged in the 1960s (Roy and Vanderpooten, 1995). The terms were used inter-changeably until clarification was made by Roy (1990). The distinguishing feature of the 'aid' approach is the involvement of stakeholders in the process (Ostanello, 1997). MCDM is an extension of multi-criteria analysis for decision problems that focus on 'making' decisions in the presence of multiple, usually conflicting, criteria (Roy, 1990; Zanakis *et al.*, 1998).

In this research, the use of MCDA was advocated for its implication of 'aiding' decision making rather than 'making' decisions. This concept is particularly important as the principle aim of using the MCDA method is to help DMs to learn about the problem situation, their own judgement and values. The process aims to support the DMs through the organisation, identification of issues and presentation of information to guide them to a preferred decision outcome. Although the term 'multi-criteria decision aid' implicitly refers to the outranking method developed by the French group, this is not the case in this thesis. The term was chosen in this thesis to reflect the importance of 'aiding' decision making.

Multiple attribute decision aid (MADA) and multiple objective decision aid (MODA) are two branches in MCDA. MADA usually involves a discrete decision variable and a limited number of alternatives for evaluation. MODA is concerned with identifying the best choice from an infinite set of alternatives under a set of constraints. In MODA, each criterion is associated with an objective, whereas in MADA each criterion is associated with a discrete attribute (Hwang and Yoon, 1981; Zeleny, 1982; Yoon and Hwang, 1995). The structure of MCDA branches is illustrated in Figure 2.3. The focus of this research is in MADA because the decision problems in urban water management generally involve a finite number of alternatives. Further justification for the selection of a specific MCDA method is provided in Section 2.4.3 p.35.

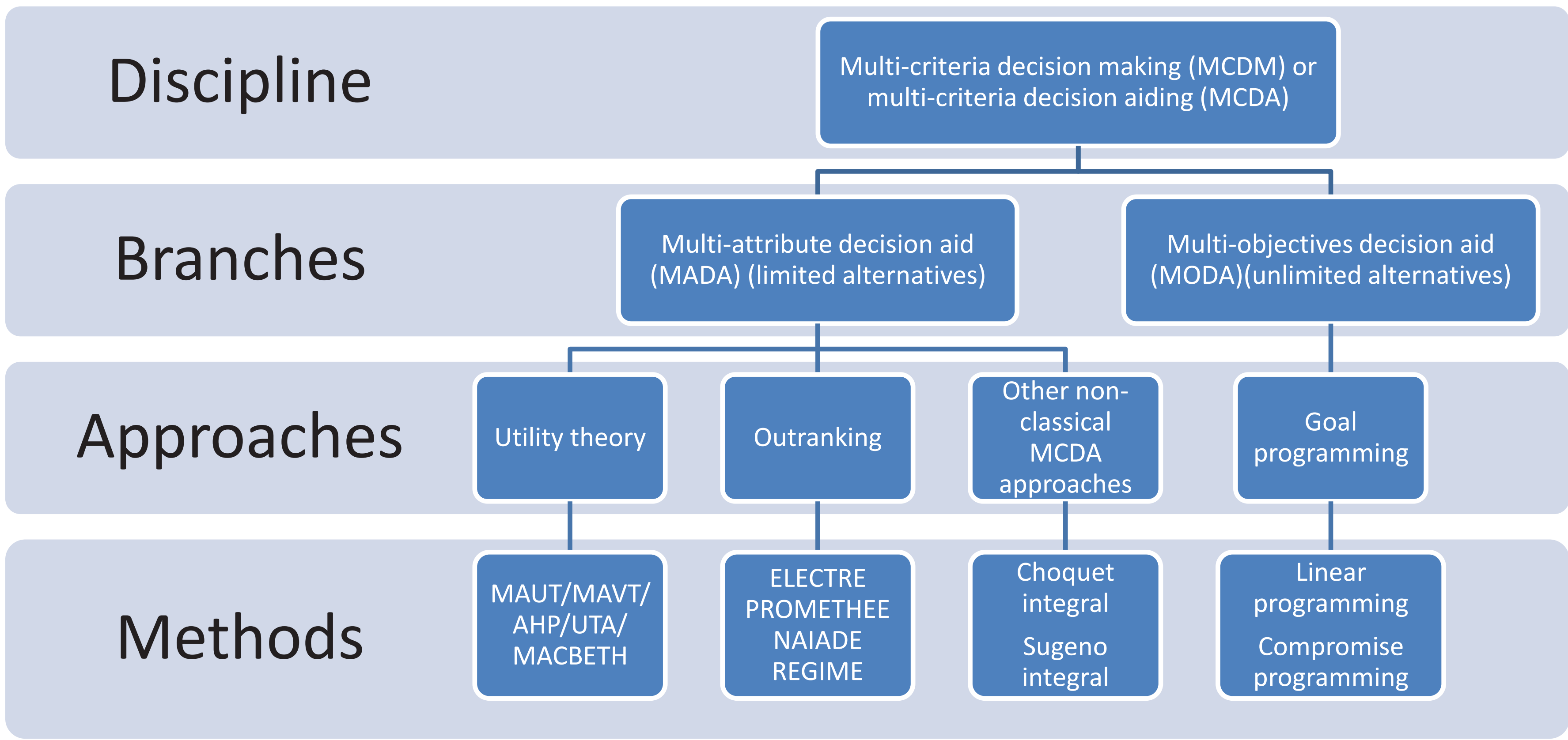


Figure 2.3 Structure of MCDA branches, approaches and methods

MAUT – Multi-attribute utility theory; MAVT – Multi-criteria value theory; AHP – Analytical Hierarchy Process; UTA – Utility Theory Additive; MACBETH - Measuring Attractiveness by Categorical-Based Evaluation TecHnique; ELECTRE - ELiminiation Et Choix Traduisant la REalite; PROMETHEE - Preference Ranking Organisation METHod for Enrichment Evaluations; NAIADE - Novel Approach to Imprecise Assessment and Decision Environments

2.4.1 MCDA process

The process of MCDA can take many forms to suit different purposes (e.g. to put forward a recommendation, to establish a monitoring procedure or to assess options). Different interpretations of the MCDA process can be found in the literature (Resource Assessment Commission, 1992; Hajkowicz *et al.*, 2000; Lawrence *et al.*, 2001), but it can be described as a non-linear recursive process containing the following main phases (as outlined in Figure 2.4) (Guitouni and Martel, 1998; Belton and Stewart, 2005):

- *Structuring the decision problem* – concerned with planning and identifying DMs, stakeholders and criteria for monitoring changes
- *Preference elicitation and modelling* - relates to the construction of a preference model to reflect the DMs' preferences
- *Aggregation* - deals with specific forms of analysis that synthesise information to produce useful recommendations for decision making
- *Recommendation* - exploiting the aggregation and making recommendations.

Together the second and the third steps (preference elicitation and modelling and aggregation) are given the general expression *decision support methodologies* (DSM). Different MCDA methods generally differ by elicit preference and aggregation procedure; thus this special terminology, DSM, is given to collectively describe these procedures or methods. A more detailed generic MCDA process is show in Figure 2.5.

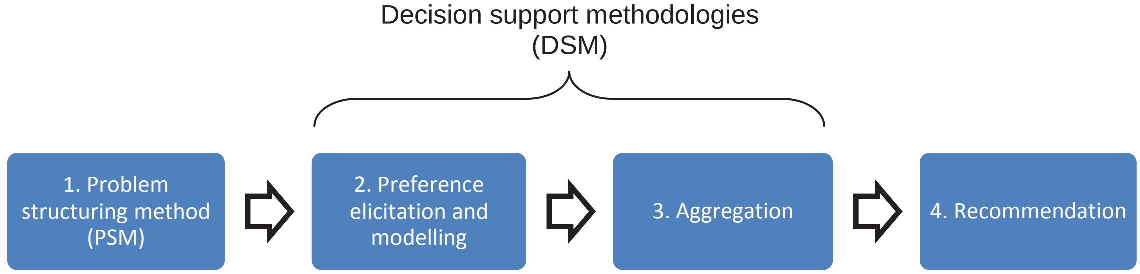


Figure 2.4 Key phases of MCDA

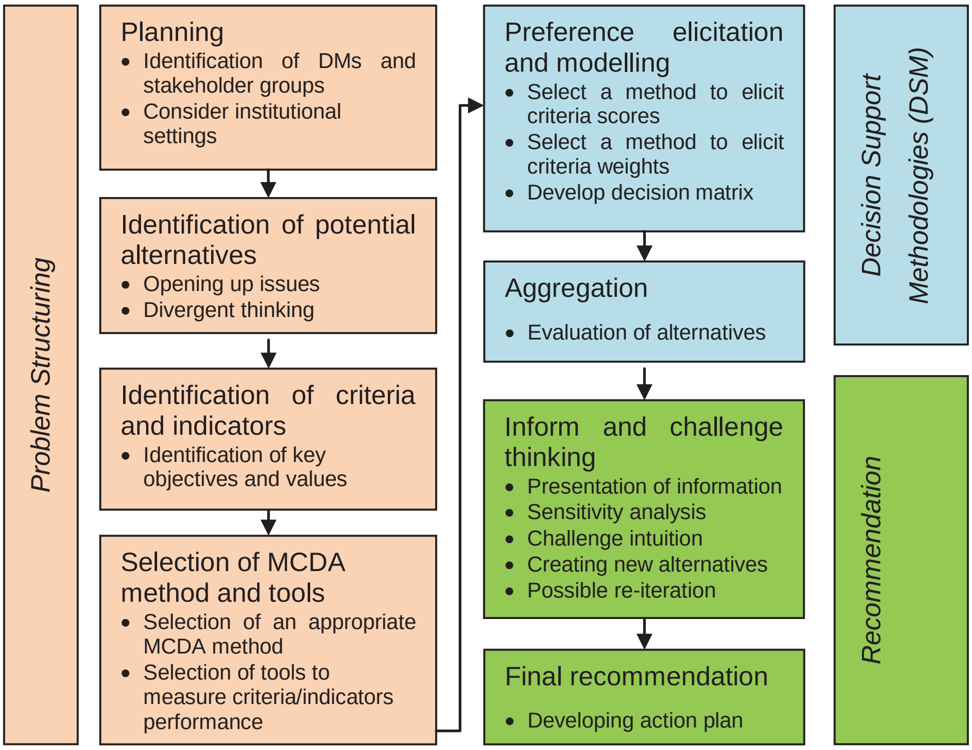


Figure 2.5 Generic MCDA process within a decision support framework

2.4.2 Decision support methodologies

At the heart of MCDA is the DSM. Selecting an appropriate MCDA approach depends on the selection of the DSM. Since MCDA approaches differed by their DSM, the types of DSM can be classified by:

- *Value measurement* (American school)[1] – the intention of this approach is to associate a real number (or '*value*') *v(x)* with each alternative in such a way that alternative a is judged to be preferred to alternative b if $v(a) > v(b)$. The approach seeks to establish the value based on the measurement of criteria performances and criteria relative importance. These two variables are aggregated to produce the value output $v(x)$.
- *Outranking methods* (European School)[1] – the outranking approach seeks to compare alternatives by balancing the relationship between the alternatives' poor performing criteria and well performing criteria. The alternatives are evaluated in a pairwise comparison fashion with respect to each criterion. The output of an outranking analysis is not a real number (value) but an outranking relationship for

[1] Value measurement (mainly attached to the method of multi-attribute value theory (MAVT) or more generally multi-attribute utility theory (MAUT)) is widely used in the United States. The first MAUT is first described in detail in award-winning book by the American Keeney and Raiffa (1976). In contrast, the outranking methods have been devised and applied mainly in Europe. For this reason, this particular branch of MCDA is frequently referred to as the 'European school'.

each alternative. An outranking relationship dictates two aspects: (1) how strongly an alternative *a* is preferred over an alternative *b* if taking into account all available information; and (2) how strongly alternative *a* is not preferred over an alternative *b*. Alternative *a* is said to be preferred over *b* if there is a strong enough argument that *a* is at least as good as *b* without any strong argument otherwise.

- *Goal programming* – this approach seeks to find an optimum alternative that has the closest distance to the goals or desirable levels of achievement set for the criteria.

A review of these three approaches together with the non-classical MCDA approaches is presented in Appendix A. For more in-depth description of each approaches and their variants, Figueira *et al.* (2005) offers a state-of-the-art review of MCDA, including methodologies, applications and software.

2.4.3 Justification for the DSM selection: value measurement

With the vast number of MCDA methods available, there is no one superior method that outperforms the others. Choosing a suitable MCDA method for a specific problem is a worthwhile problem to consider before proceeding on to the decision making process. The first two approaches (utility theory and outranking) belong to MADA and the last approach goal programming is part of the MODA branch in which the decision alternatives are considered to be infinite. Since a finite number of alternatives is considered in urban water decision problems, only methods from the MADA branch are considered. Therefore, goal programming is not considered and the other two MCDA approaches are left for consideration.

There are now two candidates left for the selection of a preferred MCDA approach (value measurement and outranking). The selected preference model is value measurement. Value measurement is chosen because is one of the most widely applied MCDA methods. Since its origins in the late 1960's, value measurement has strongly influenced developments in this field. This influence is also mirrored by the Australian water sector. The five Australian long water strategies reviewed under Section 2.5.1 p.39 have all adopted a value measurement approach. In addition, 45 journal publications of MCDA applications in water resources management were reviewed under Section 2.5.1 p.39. It was found that 24 articles used value measurement, followed by 12 articles which used outranking methods and 9 articles using goal programming methods. Further justifications for the selection are explained in the following text using the guidelines from Guitouni and Martel (1998).

Guideline: *Consider the DM's 'cognition' (way of thinking) when choosing a particular preference elucidation mode. If he or she is more comfortable with trade-offs, why use pairwise comparisons and vice versa?*

A range of criteria weighting techniques can be incorporated into value measurement such as direct assignment, swing method, trade-off and the entropy. In contrast, outranking is solely based on pairwise comparisons (see Appendix B for description of different criteria weighting techniques). In value measurement, criteria weights and criteria scores are distinguished explicitly (Belton, 1986), but not in the case with outranking. The 'weight' is embedded in the outranking relationships constructed for the alternatives (Roy and Vanderpooten, 1995). Therefore, the concept of criteria weights and criteria scores may be more intuitive to DMs compared to outranking relationships. Transparency is an important factor considered in the selection of an appropriate preference model. The preference model must be suitable for use in the decision workshop setting, because the researcher works directly with the DMs for obtaining data. Outranking methods such as ELECTRE require inputs such as concordance and discordance threshold levels and the construction of outranking relationships, which may not be intuitive to the DM.

It is recognised that both methods strive to construct a new perception of the problem and a new preference structure on it; their legitimacy depends on the acceptance by the DMs (Stewart and Losa, 2003). The weighted sum under value measurement is one of the simplest forms of aggregation model that is widely used in the field of urban water decision making in Australia. Direct assignment of weights or making trade-offs can be easily explained to and understood by DMs from a variety of backgrounds. As suggested in the review of long-term water strategies (Section 2.5.1 p.45), the majority of the plans adopted a weighted sum approach. Based on this observation, the value measurement approach is an appropriate model of supporting decision making for urban water management in Australia.

Guideline: *Choose the method that can handle properly the input information available and for which the DM can easily provide the required information; the quality and the quantities of the information are major factors in the choice of the method.*

Both the value measurement and outranking approaches can assimilate quantitative and qualitative information. The issue of greater importance is the quantity of judgement required. One of the main drawbacks of outranking is the large number of judgements required from the DM for pairwise comparisons — $n(n-1)/2$ comparisons for n criteria — whereas utility measurement requires less judgement for $n > 5$ ($2n$). Research in decision making behaviour has shown that DMs tend to eliminate some of the available alternatives quickly to reduce cognitive strain (Payne, 1976). This could impose an indirect negative influence on the quality of the information obtained from the DM.

Guideline: *The compensation degree of the MCAP method is an important aspect to consider and to explain to the DM. If he/she refuses any compensation, then many MCAPs will not be considered.*

In most multiple criteria decision problems, DMs have to accept less achievement for some criteria in exchange for more achievement in others. This logic is commonly known as compensatory. In urban water management, decisions were rarely made on extreme grounds (i.e. no compensatory trade-offs). Both value measurement and outranking approaches allow for compensation (Stewart and Losa, 2003), but the concept of compensation is more apparent in value measurement via the use of value trade-offs (sacrifices in some criteria performances in return for gaining performances in other criteria). It is easier to explain the concept of compensation to a DM because it is intuitive when making trade-offs between criteria's achievements. For pairwise comparisons, comparisons are made between alternatives with respect to a criterion. Therefore, it may not be obvious to the DM the degree of compensation between criteria achievements.

2.5 Shortcomings with MCDA in urban water management

Considerable effort has been devoted in the development of decision support frameworks that adopt a MCDA approach to enhance the quality of decision making over the last decade (Hämäläinen *et al.*, 2001; Joubert *et al.*, 2003; Ashley *et al.*, 2004; Makropoulos *et al.*, 2006; Vàzquez and Rosato, 2006; Giupponi, 2007; Lundie *et al.*, 2008a). Despite the widespread availability of decision support frameworks, the usefulness of these frameworks is uncertain (Sharda *et al.*, 1988; Sainfort *et al.*, 1990; Newman *et al.*, 2000; Mysiak *et al.*, 2005; Hajkowicz and Higgins, 2008). Often a decision adopted in the end is different from solutions obtained from the MCDA models. There are gaps between the challenges in real world decision making and the underlying formal mathematical theories behind MCDA approaches.

To identify the gaps that are associated with the use of MCDA in urban water decision making, the author carried out an extensive review of the literature in a systematic manner (Figure 2.6). First, the author identified key trends from relevant review papers on MCDA. The identified key trends provided ideas about the current gaps in MCDA applications. Secondly, an in-depth review of journal publications on MCDA applications was carried out to confirm the validity of the identified gaps. Lastly, some of the long-term water strategies developed by various water authorities in Australia are reviewed with respect to the identified gaps. These gaps formed the bases of the shortcomings that this thesis set out to address.

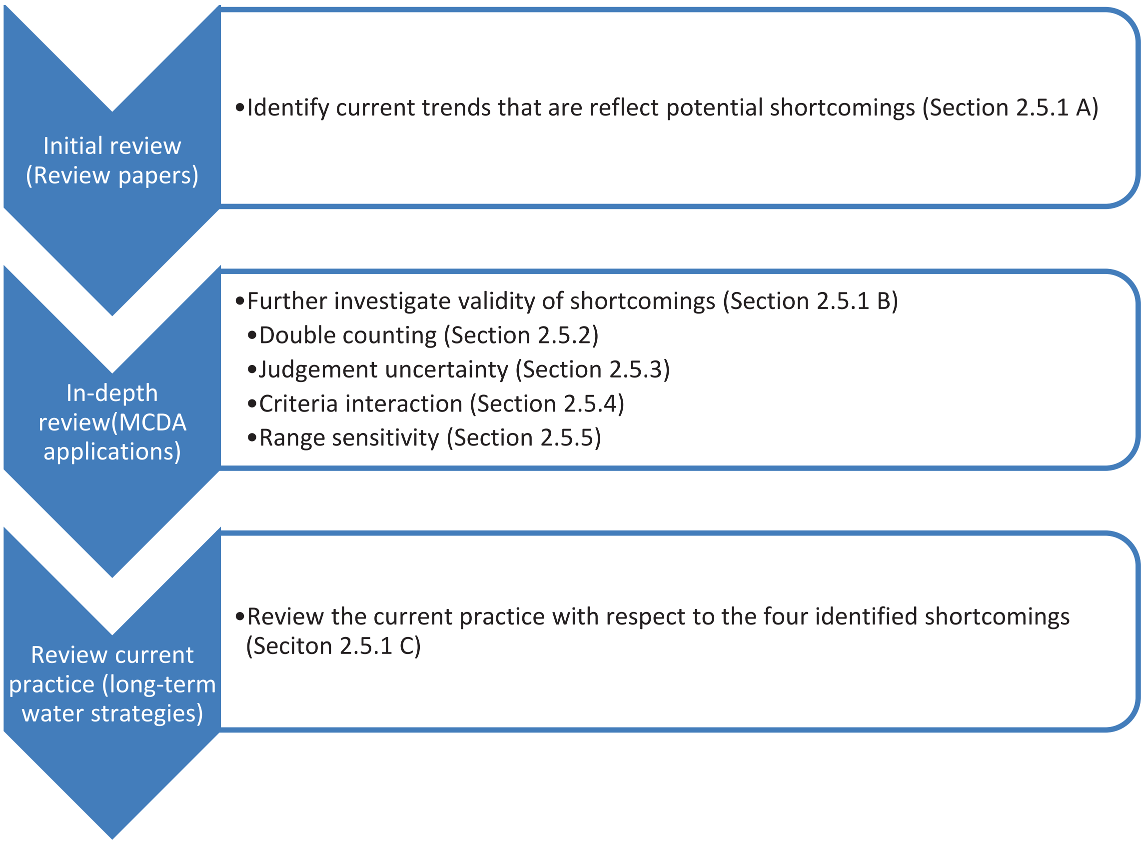


Figure 2.6 Process of identifying shortcomings with MCDA

2.5.1 Review of MCDA applications in urban water management

This section presents the findings from reviewing the following types of publications:

- MCDA review papers
- MCDA applications in water management
- Long-term water strategies developed by various Australian water authorities

<u>MCDA review papers - identify key trends</u>

Thirteen review papers on MCDA applications in various fields were reviewed. A summary of the review papers are presented in Appendix C1. The key trends in the applications of MCDA to various natural resources management were identified:

- ***Accountability, transparency, conflict management, stakeholder engagement*** – Common reasons for adopting MCDA are the provision of accountability, transparency and conflict resolution stakeholder engagement and the use of decision theory to inform choice to the decision making process (Söderberg and Kain, 2002; Vàzquez and Rosato, 2006; Hajkowicz and Collins, 2007).

- ***Prefer less complex MCDA*** **–** There seems to be a growing emphasis on using less complex MCDA methods because most of the urban water management decisions are at the strategic level normally undertaken by non-experts in the field of MCDA (Smith and Theberge, 1987; Hajkowicz and Collins, 2007).
- ***No strict relationship between methods and problems*** **–** It is difficult to find the most suitable MCDM methodology for a specific problem. There is no strict relationship between methods and problems. The choice is also dependent on the availability of information and its quality (Tecle, 1992; Hobbs and Meier, 1994; Salminen *et al.*, 1998; Zanakis *et al.*, 1998).
- ***Emphasis on problem structuring*** **–** Many achievements have been obtained in the application and development of MCDM methods. The trend now is less on the development of new methods but towards the development of integrative frameworks that would include more emphasis on the initial structuring of the decision problem (Keeney, 2004; Hajkowicz and Higgins, 2008).
- ***Limited uncertainty management*** – Uncertainty in decision making generally refers to the lack of knowledge about the consequences of a particular choice and the common treatment is sensitivity analysis (Rios Insua and French, 1991) or probabilistic distribution. However, there are other forms of uncertainty presented in environmental decision making such as uncertainties related to the guiding values (Söderberg and Kain, 2002) and preferential judgement (Stewart, 2005), which cannot be managed by probabilistic distribution (Klir, 1989). These uncertainties are generally not well managed.
- ***Ignore relationships between criteria*** **–** There are inherent linkages between criteria (Niemczynowicz, 2000), but in many cases, criteria are aggregated by assuming that they are fully independent which is unrealistic (Smith and Theberge, 1987).
- ***Decision results sensitive to criteria measurement range*** **–** The analysed decision results are sensitive to the methods adopted to elicit criteria weight method and to standardise criteria scores (Stakhiv, 1992; Fischer, 1995).

Review MCDA applications

In light of these findings, it is evident there is strong value in the application of MCDA to support water resources management problems (first three points highlighted above, but there remain challenges in the implementation (last four points highlighted above). To investigate these four issues more closely, 45 journal publications of MCDA applications in water resources management and 13 review articles on MCDA application in natural resources management were selected and examined in detail. A summary of the articles is presented in Appendix C. These articles were reviewed with the question, '*What is the treatment of the four issues: problem structuring, uncertainty management, criteria interaction, range sensitivity*?'. Different treatments were applied to different applications, as such, the author devised a set of code to differentiate the differ treatments for each of the three issue. The codes and the corresponding treatment options are summarised in Table 2.2. The findings of the review are summarised in Table 2.3. The results are presented as the percentage of the total publications under each type of treatment. A consolidation of the findings is contained in the sections below:

- Most of the publications (47%) did not adopt any decision support framework to assist in the structuring of the decision problem (e.g. identification of stakeholders, selection criteria, selection of MCDA method and manipulation of recommendation), only a quarter of the review publications (27%) did. The remaining quarter structured the decision problem through publication consultation (interview or workshop with the communities) and discussion with DMs (Table 2.3). A specific consequence of not using any problem structuring method in a decision problem is *double counting*. The rationale for this specific concern is detailed in Section 2.5.2 p.46
- A majority of the publications adopted sensitivity analysis (58%) to address the uncertainty associated with criteria weights judgement and criteria scores assignment. A smaller portion of the publication (18%) addressed the same issue with the use of fuzzy set theory (Table 2.3). A specific form of uncertainty called the *judgement uncertainty* is generally not addressed in urban water decision problem. The rationale for this specific concern is detailed in Section 2.5.3 p.48.
- Almost all publications (98%) did not consider the case for criteria interdependency by assuming the criteria to be fully independent (Table 2.3). This shortcoming is called *criteria interaction*. The rationale for this specific concern is detailed in Section 2.5.4 p.54.
- A majority of the publications use the method, construction of a qualitative scale to standardise the criteria scores (35%) (Figure 2.9). Most adopted a direct assignment method (35%) using either a numerical scale (0–1 or 0–100 point) or a qualitative

scale (extremely good to extremely bad) to rate the importance of the criteria (Figure 2.8). The shortcoming associated with this finding is the *range sensitivity*. The rationale for this specific concern is elaborated in Section 2.5.5 p.55.

Table 2.2 Code to identify different treatment methods for the four shortcomings

Code	Problem Structuring	Uncertainty	Criteria Interdependency
1	*Use of decision support framework* – the type of decision support framework are specified which assist the DMs to structure the decision problem	Use of fuzzy set theory	Assume criteria interdependency
2	*Through public consultation or workshop with DMs* – no details on the adoption of any decision support framework but the problem was structured through stakeholder engagement with the public and/or DMs	Sensitivity analysis of criteria weights and/or criteria scores	Assume criteria independency
3	*Method not specified*	Not addressed	-

Table 2.3 Types of treatment to the three identified shortcomings

Code (Total publications, n=45)	Problem Structuring	Uncertainty	Criteria Interdependency
1	27%	18%	2%
2	27%	58%	98%
3	47%	24%	-

Note: Refer to Table 2.2 for the explanation of the code for each type of shortcoming

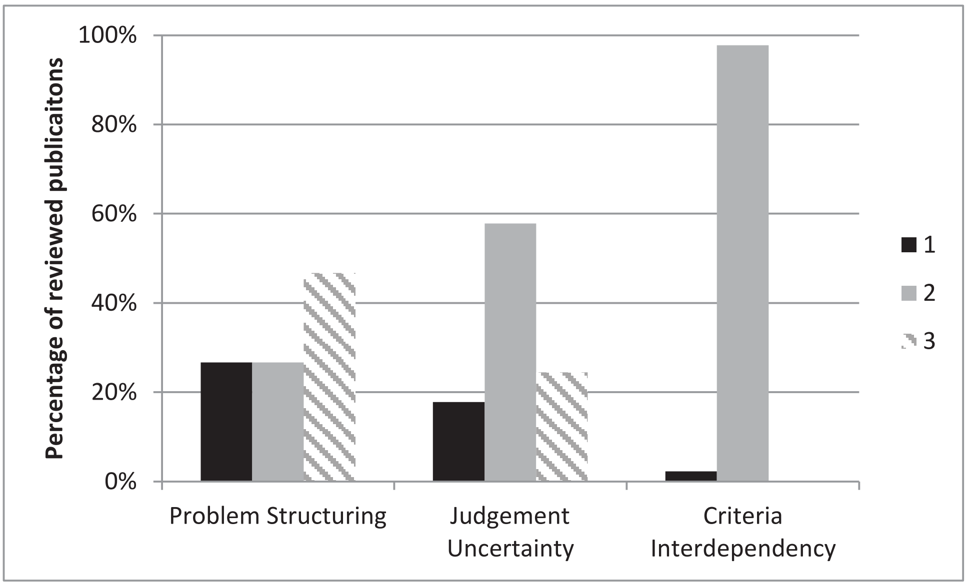


Figure 2.7 Journal article review: summary of treatment option to the three issues

Note: Refer to Table 2.2 for the explanation of the code for each type of shortcoming

In the same journal article review, the methods that were used to elicit criteria weights and to standardise criteria scores were also reviewed. Details on each of the criteria weighting methods and criteria scores standardisation are presented in Appendix B. The criteria weighting methods are briefly summarised here:

- *Direct assignment* – this method requires the DM to assign the weights directly using cardinal values or ordinal ranking using qualitative values.
- *Swing* – this method considers each criterion from its worst value to its best value. The amount of ‘swing’ to move from the worst value to the best value is the corresponding criteria weight.
- *SMART (simple multi-attribute rating technique)* – this is variant of the direct cardinal assignment method but ratio judgements are used instead.
- *Trade-off* – two criteria are compared at a time to identify the indifference point in the trade-off between the two criteria while the other remaining criteria are considered to be equal.
- *Pairwise comparison* – each criterion is compared against each other criterion in pairs. The most well-known method is Saaty’s Analytic Hierarchy Process (AHP).
- *Value tree* – the decision problem is structured as a value tree (a multi-level hierarchy of criteria) and the weights are assigned to different levels of the tree. The sum of sub-criteria weights should equal the weight of the parent criterion.

- *Distance to goal* – the normalised criteria score is measured based on the distance away from an ideal target. This technique involves the assignment of an ideal target that is an achievement of a criterion that DM would like to realise.
- *Entropy* – the central idea of this method is that a criterion's relative importance is measured by its entropy or 'dispersion'.

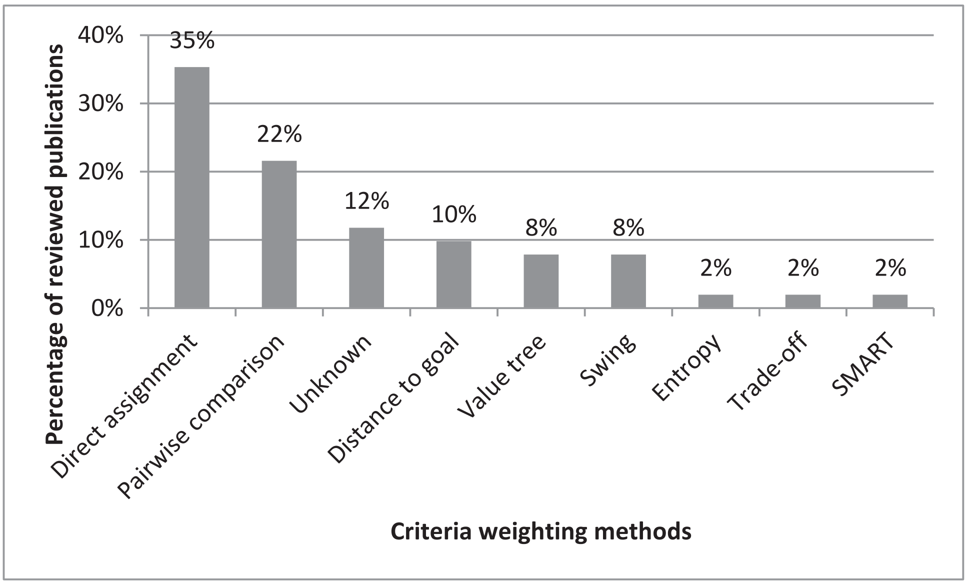


Figure 2.8 Journal article review: summary of criteria weights elicitation methods

The criteria score standardisation are briefly summarised here:

- *Normalisation* – concerned with constructing partial value functions to measure the relative performance level of each selected criterion. There are three types of partial value functions: (1) monotonically increasing; (2) monotonically decreasing; (3) non-monotonic.
- *Construction of qualitative scale* – a qualitative measurement scale can be constructed based on expert judgement.
- *Direct rating of alternatives* – rating the alternatives directly with respect to each criterion can be seen as the construction of a measurement scale.

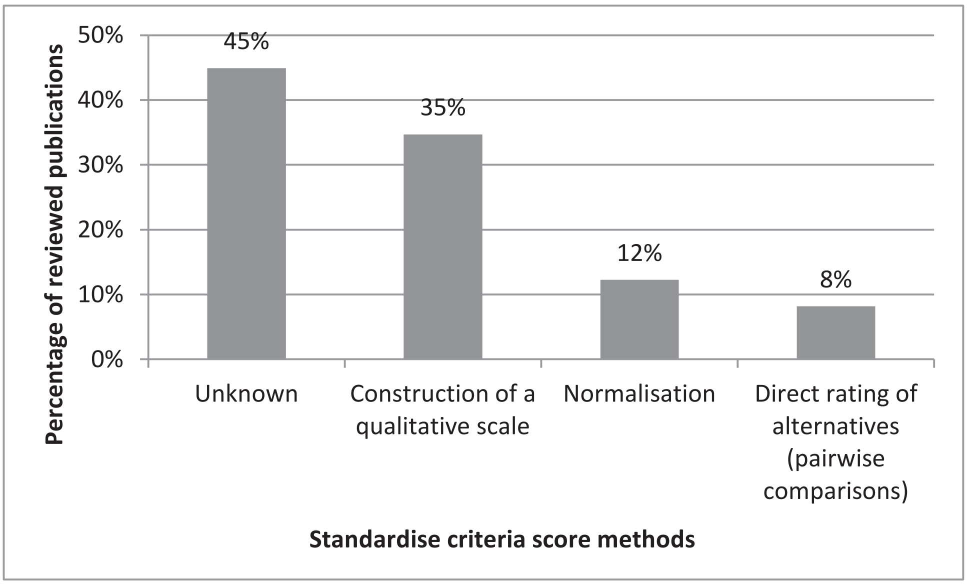


Figure 2.9 Journal article review: summary of criteria scores standardisation methods

So far, the literature review identified four gaps broadly without going into detail of the exact problem. The next four sections elaborate more deeply into each of the identified issue. The shortcomings within the four gaps are briefly summarised as follows:

- *Double counting (problem structuring)* – over-estimation of certain aspects when the chosen criteria are redundant.
- *Judgement uncertainty (uncertainty)* – arises from incomplete knowledge of the consequences of actions, imprecision and over simplification.
- *Preferential independency (criteria interdependency)* – preference for criteria is assumed to be independent of each other.
- *Range sensitivity* – most applications use a qualitative constructed scale with arbitrary label as a mean to assign criteria weights or criteria scores without reference to a scale specific to the criterion.

Review current practice in urban water management

Five published long-term water strategies are reviewed with respect to the four shortcomings identified in Table 2.4: Gold Coast Waterfuture (Gold Coast Water, 2005), Gosford-Wyong Council Water Authority’s WaterPlan 2050 (Gosford-Wyong Council’s Water Authority, 2006), Western Australia’s Water Corporation’s Water Forever (Water Corporation, 2008), Government of South Australia’s Water For Good plan (Government of South Australia, 2009), Goulburn Valley Water’s GVW2055

(Goulburn Valley Water, 2007) and Melbourne Water (Brown *et al.*, 2010). A summary of the identified shortcomings in a number of long-term water strategy plans in Australia is provided in Table 2.4.

2.5.2 Problem structuring: double counting

Problem structuring is concerned with the identification of a number of factors, including key concerns, objectives, stakeholders, options. It is the identification of these factors which should constitute the agenda for further discussion and analysis (Rosenhead, 1989). Among all of these factors, one of primary focus in this thesis is the selection of criteria, which is outlined in the research scope in Section 1.4 p.5. The other factors such as identification of stakeholders and options involve institutional factors which are beyond the scope of this research, but the selection of criteria has a direct influence on the subsequent decision model construction.

There are guidelines for the selection of criteria. They are generally in the line of meeting the following considerations (Keeney, 1996; Belton and Stewart, 2005):

- *Value relevance* – the DMs should be able to make the link between the criterion to high level objectives
- *Understandable* – the concept presented by the criterion should be shared by all DMs to avoid confusion
- *Measurable* – the criterion should be measurable and decomposable to a level detail which allows this
- *Complete* – all important aspect of the problem are captured
- *Operational* – the effort required to ascertain the information is reasonable
- *Concise* – keeping the level of details to the minimum required
- *Non-redundancy* – the same factor is accounted for in more than one criterion.

Table 2.4 Shortcomings with the assessment methodology adopted by the different water strategies

Water strategy	Double counting	Uncertainty / Criteria weights + scores evaluation	Criteria interaction
Goulburn Valley Water GVW2055 (Goulburn Valley Water, 2007)	Two criteria shared common attributes: Effectiveness – ML[2] saved. Efficiency – $/ML.	Uncertainty in the use of qualitative scale (extremely bad to extremely good) represented by precise numerical scores (-5 to 5) which could be open to different interpretations.	Two criteria were partially interdependent: Level of service. Acceptable water quality.
Gold Coast Waterfuture (Gold Coast Water, 2005)	Two criteria shared common attributes: Potential impact on the environment (change of biodiversity in terrestrial/aquatic environment). Loss of high value ecosystem (loss of terrestrial habitat).	Uncertainty in the use of scoring scale (poor to good) represented by precise numerical scores (1 to 5) which could be open to different interpretations.	Two criteria were partially interdependent: Loss of vegetation. Relative value of ecosystem significantly disturbed (significant flora/fauna species affected).
Water Forever (Water Corporation, 2008)	Two criteria double count the importance of land: Physical footprints which measured the hectares of vegetation cleared. Capacity to enhance the environment (impacts on national parks, reserve, State forests etc). Two criteria double count volume (kL[3]): Energy intensity (kWhr[4]/kL) Net economic cost ($/kL).	Uncertainty in the use of 0 to 4 scoring scales which could be open to different interpretations.	Two criteria were partially interdependent: Reliability of services which consider the ability to deliver the expected water volumes. Rainfall dependence.
Water for Good (Government of South Australia, 2009)	Two criteria double count the importance of energy use: Energy cost. Value of greenhouse gas emission.	Uncertainty in the valuation of social, environmental costs using costs-benefits approach.	Two criteria were partially interdependent: Value of greenhouse gas emission. Energy use.
WaterPlan 2050 (Gosford-Wyong Council Water Authority, 2006)	The benefits and costs of environmental flow are double counted in financial assessment and environmental impact assessment.	Uncertainty in the evaluation of qualitative criteria using constructed qualitative function.	Two criteria are partially interdependent: Storage recovery. Impact of release from Mangrove Creek.

[2] ML = megalitre
[3] kL = kilolitre
[4] kWhr = kilo watt hour

All of the above considerations are achievable to different degrees but there are no hard and fast guidelines as to how to eliminate double counting due to redundancy (Belton and Stewart, 2005). Double counting occurs when the chosen criteria are at least partly redundant and key criteria are not included respectively (Schankerman, 1981). This problem is prevalent in most environmental assessments, particularly when dealing with natural resources due to the inter-disciplinary nature of the problem.

In economics, the problem of double counting is formally captured as an error in the value of an economy's product by accounting the same intermediate goods more than once (Mankiw, 2007). For example, in the making of a car, metal is called the intermediate good and the car is the final good. The economy product should only include the value of the final goods. Adding the market value of the metal to the market value of the car would be double counting because the value of the metal is included in the car's market value. Saaty (1994a) defined this problem as 'the occurrence or use of the weight of a criterion more than once in the weighting of the alternative'. This issue is reported in various assessments of environmental services (Odum, 1996; Costanza *et al.*, 1997; Rowley *et al.*, 2009; Searchinger *et al.*, 2009). For example, having both global greenhouse gas impacts and primary energy input as measurements for environmental impact can over-rate the impact of coal derived energy which is factored in both primary energy and greenhouse gas impacts.

The opposite of double counting is the problem of undercounting which occurs if the list of fundamentally important criteria was not included. This depends on the scope of criteria that the DM sets out to examine, although similar to double counting, this problem can be eliminated by carefully examining each proposed criterion during the problem structuring stage of MCDA process. Hence, the issue of undercounting is not considered in this thesis.

2.5.3 Judgement uncertainty

The process of decision making is a dynamic social process in which human judgement, values and expectation would change and evolve through the process of discussion and negotiation. Therefore, the credibility of the decision outcomes determined by MCDA methods can be affected by the embedded uncertainty if not stated explicitly or dealt with in the model. The embedded uncertainty can appear in various forms such as incomplete knowledge of the consequences of actions, imprecision and over simplification (Bellman and Zadeh, 1970; French, 1995; Zimmermann, 2000).

Similar to uncertainty, variability is an inherent characteristic in urban water decision making. These two terminologies can be easily used interchangeably but they represent two distinct concepts. It is important to differentiate these two concepts in order to address the problem of uncertainty more precisely. Variability in the context of decision making refers to the range of possible values for any measurable characteristic. This can be the differences in interests and values of the stakeholders (e.g. the difference in attitude towards risk for individuals). In contrast, uncertainty refers to incomplete knowledge about the decision making problems. The same understanding of variability and uncertainty is applied in the following description of uncertainty.

There is little common interpretation on the categorisation of uncertainty in the literature as different authors offered different explanations. The categorisation of uncertainty is generally described by the terms types, sources and causes. These terms are used synonymously in the literature. However, in order to make sense in the vastly different interpretations of uncertainty and to specify clearly the types of uncertainty that this research was focused on, the author makes a differentiation between sources and causes of uncertainty:

- *Sources of uncertainty* – refers to the context in which uncertainty occurs; similar to asking the question, "In regard to what context is the uncertainty associated?" (Sigel *et al.*, 2010). The sources of uncertainty are the subject matter in which uncertainty is involved.
- *Types or causes of uncertainty* – refers literally to the causes of uncertainty which can be attributed to the lack of knowledge, error in measurement or conflicting information.

The following further describe the two categorisations of uncertainty in decision making. The referenced literature described in the following did not make the differentiation between sources, causes or characterisation of uncertainty. The author applied the differentiation to their interpretations of uncertainty in order to highlight the relationships between the two.

Friend and Hickling (2005) outlined three *sources of uncertainty* in :

- *Uncertainty about the working environment* (UE) – refers to uncertainty associated with information obtained, such as doubts about accuracy and extent of knowledge.
- *Uncertainty about the guiding value* (UV) – refers to the uncertainty associated with the selection of criteria and the form of judgement adopted (i.e. ordinal or cardinal scales).
- *Uncertainty about the related decision* (UR) – refers to the concern that the decision under consideration can relate to other inter-connected decisions. This can extend to the co-ordination between stakeholders as inter-connected decisions may affect a wider range of stakeholders. Thus this can lead to uncertainty in relation to which stakeholder groups' opinions to advocate.

Zimmerman (2000) outlined six *causes of uncertainty* in decision making:

- *Lack of information* – this can be attributed to two possible reasons: a) the available information is insufficient to describe the situation deterministically, or b) the DM does not have or is not willing to gather sufficient information to make an exact description even if it is possible for various reasons (i.e. too costly to obtain required information). Hence the description of the situation is an approximation.
- *Abundance of information* – this situation occurs when the amount of available data exceeds the ability of the DM to comprehend it all. According to research in decision behaviour, the DM will adopt some mechanisms to eliminate excess information to reduce the complexity of the information (Payne, 1976). The DM will focus on information that seems to be most important to them, whilst other information is disregarded and hence induces uncertainty.
- *Conflicting evidence* – uncertainty of this cause is related to the available information that points to different directions which may increase conflict. This can also be due the fact that the information available is wrong or of little relevance.
- *Ambiguity* – this occurs when certain linguistic information has different meanings and it is not clear to the DM as to the exact interpretation. This type of uncertainty can be eliminated by clarification or adding more information.
- *Measurement* – this is referring to engineering measurement and the uncertainty associated with its quantity and scale adopted in the measurement. All numerical representation using engineering measurement such as measurement of weights and

temperature are indications of the real physical properties. Although with the advancement of technology, there is no guarantee the properties of any physical systems can be measured perfectly. This source of uncertainty, however, is generally in orders of magnitude less than other uncertainties.

- *Subjective beliefs (imprecision)* – the interpretation of information is affected by some kind of subjectivity in human understanding, which can be referred to as beliefs. The subjective belief of an individual can be unknown to other stakeholders in the decision making progress. The author refers to this subjectivity as *imprecision* in conveying the beliefs and this is what constitutes the uncertainty. It is perfectly normal for each individual to hold different beliefs as this is part of human nature. The problem is when the subjectivities are unknown to each other in the decision making process or conveyed vaguely because of the language used. This imprecision is different from ambiguity in the sense that a belief is defined imprecisely but ambiguity refers to multiple meanings. Consider an example to illustrate the difference between vagueness and ambiguity: the performance of a criterion can be rated as 'low'. It can be difficult for the DM to interpret the meaning of this rating as the problem associated with this lies with the imprecise definition of 'low' and not with the multiple meanings of low, which is represented by the problem of being ambiguous.

There are two common themes underlying the two categorisations (sources and causes of uncertainty). One of the common themes can be distinguished as *internal uncertainty*, which relates to the structure of the model adopted and the judgemental inputs. The other theme is *external uncertainty*, which relates to the unknown consequences of action incurred by the external environment outside the control of the DM (Belton and Stewart, 2005; Stewart, 2005). To provide a more comprehensive understanding of the relationships between the sources and causes and uncertainty, a summary of the different categorisations according to internal and external uncertainty are presented in Table 2.5.

Table 2.5 Summary of uncertainty categorisations by internal and external uncertainties[5]

	Internal	External	
Sources of uncertainty	Uncertainty about guiding values (UV)	Uncertainty about the environment (UE)	Uncertainty about related decisions (UR)
Causes of uncertainty	Ambiguity in the meaning of guiding values	Lack of information about the randomness inhere in processes (i.e. changes in climate)	Abundance of information generated by considering other inter-connected decisions
	Imprecision in the qualitative assessment of criteria performance	Measurement error in the quantitative criteria performance	Conflicting opinions from stakeholders

Rationale for the focus on internal uncertainties

Ambiguity and vagueness associated with guiding values and judgement are the main causes for internal uncertainties. The focus of this research is related to internal uncertainty because this is an area very seldom modelled in the context of urban water decision making (Lai *et al.*, 2008). This is not to diminish the importance of external uncertainties but coverage of this topic using probability models is well addressed (Stewart, 2005; Hyde, 2006).

Based on the review of five published long-term water strategies in Australia (Table 2.4), internal uncertainty is introduced by the use of qualitative assessment for rating criteria performance. The associated values of the linguistic terms are simplistically represented by precise numerical values which may not reflect the vagueness inherent in the linguistic terms used (i.e. low performance, very low performance). Uncertainty about the numerical representation of linguistic judgement terms is generally overlooked. The influence of this can be significant since linguistic assessment is a major part of the assessment in urban water decision problems which rely heavily on expert judgement. The author refers to this problem as *judgement uncertainty*.

The treatment of external uncertainty related to lack of knowledge has traditionally relied on the use of probability theory. Probability theory studies the likelihood of

[5] Characterisation of the causes of uncertainty is not limited to the case defined here. The purpose of Table 2.5 is to illustrate the relationships between the sources of uncertainty and the causes of uncertainty.

random events occurring, in which the sequence of random events will exhibit certain statistical patterns. A PhD thesis by Hyde (2006) addressed this particular issue of external uncertainty due to input parameter values (i.e. criteria weights and performance scores) and the influence on final alternative rankings. Hyde adopted a probabilistic approach to account for the lack of knowledge in relation to input parameters values.

To define the problem of judgement uncertainty and its relationship with internal uncertainty more precisely, the author further divides internal uncertainty into two sources of uncertainty described as follows:

- *Problem structuring (uncertainty about meaning)* – uncertainty associated with problem structuring can take many forms, some of which are resolvable and some are not. Uncertainty about the meaning of certain terms caused by *ambiguity* is a form of resolvable internal uncertainty (i.e. what is meant by 'well-being'). Other forms of resolvable internal uncertainty include the appropriate number and level of details required for describing the criteria and alternatives.
- *Preference elicitation* (*judgement uncertainty*) – uncertainty associated with preference elicitation is less resolvable because it deals with the problem of *imprecision*. This is closely related to the elicitation values for building the preference model, which deals with imprecision in the assessment of performance values for different alternatives and trade-offs between performances on different criteria.

The first source of internal uncertainty is more relevant in the context of problem structuring and model building, dealing with issues such as the selection of criteria and alternatives. Uncertainties in relation to this problem can be minimised with careful problem structuring methods described in Section 2.6.2 p.63. The second source of internal uncertainty is more relevant in the context of value elicitation for building the preference model, and give rise to the problem of *judgement uncertainty* which is one of the problems addressed in this research. A summary of these two sources of uncertainty is given in Table 2.6.

Table 2.6 Type one and type two internal uncertainty

Sources of uncertainties	Characteristics of uncertainty
Problem structuring	Uncertainty about meaning / ambiguity Uncertainty about the depth to which to conduct an analysis (i.e. how many criteria to consider)
Preferences elicitation	Uncertainty about vague judgements linguistic terms

2.5.4 Criteria interaction

Criteria interaction is a problem in which the preference between two criteria is dependent on the preference order of other criteria. This is a common problem encountered in urban water management problems because there are a large number of factors that affect the hydrophysical, technical, economic and institutional settings of the urban water system. These factors inter-relate in a complex way such that the preference of some criteria may depend on the levels of other criteria.

Belton and Stewart (2005) illustrated the problem of criteria interaction using an example. Suppose in a water development scheme, three criteria were identified as (1) investment cost, (2) person-days of recreational facilities provided, and (3) number of invertebrate species conserved. If the investment costs were high, it may be difficult to justify a restriction on recreational access to conserve the invertebrate species from a politician's point of view. Conversely, this preference may not hold if the investment costs were low.

To avoid the complexity of this problem, one of the main underlying concepts in the utility theory approach is the *preferential independence* assumption. The condition implies that the preference between a pair of criteria (x_a and x_b) is independent of other criteria's preference order $x_{c\backslash ab}$ (i.e. $a, b \notin C$). In general, this means that for the case with more than two criteria, the preference ordering between two criteria should not depend on the levels of other criteria's performance. Although, it is recognised that assuming the preference of a criterion is independent of another criterion and/or alternative does not always hold (Fishburn and Keeney, 1975; Saaty, 1986).

The concept of preferential independence can be explained using indifference curves. A set of indifference curves which illustrate the way DMs structure their preferences in a two-dimensional evaluation space is shown in Figure 2.10 (Keeney and Raiffa, 1976). An indifference curve suggests that the trade-off between x_a and x_b is the same along any points on the curve $(x_2 \sim x_1)$. For example, if a third criterion is introduced (x_c), the preference between x_a and x_b may increase and this results in a new indifference curve $(x_3 \succ x_2 \sim x_1)$.

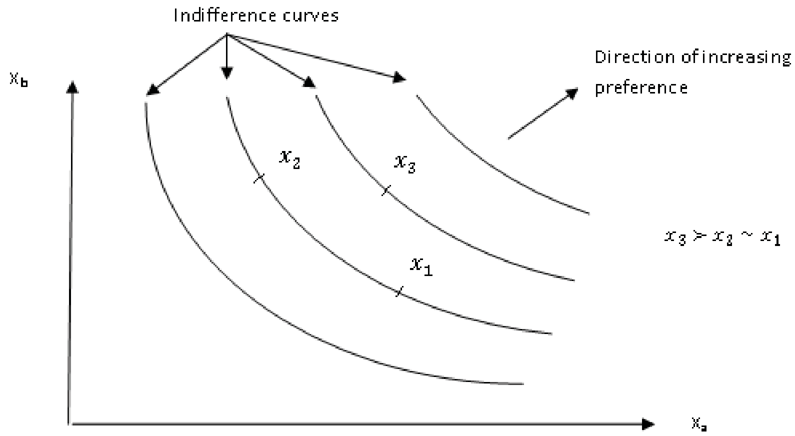


Figure 2.10 Indifference curve (Keeney and Raiffa, 1976)

The whole set of criteria C is said to be *mutually preference independent* if for the subset $I \subseteq C$ the set x_I is preference independent of $x_{I \notin C}$. Although the mutual preference independence among criteria allows for a utility function to be additive, it is not necessarily a condition that is always fulfilled (Fishburn, 1970). Grabisch (1996) used an example of evaluating high school student performances to demonstrate the case of criteria interaction. Three students were evaluated for their overall performance based on three subjects (mathematics, physics and literature) and the school wanted to focus on well-rounded students. Students who performed well in mathematics generally performed well in physics (and vice versa). Taking a weighted average would over-emphasise the students who performed well in mathematics/physics.

2.5.5 Range sensitivity

A common mistake is to assume that the elicited criteria weights are independent of the criteria measuring range (Goldstein, 1990; Pomerol and Barba-Romero, 2000; Belton and Stewart, 2005). The assignment of weight is directly related to the method of standardising the criteria scores. This range dependence of weights is referred to as *range sensitivity* (Fischer, 1995). An example taken from Fischer (1995) is presented here to illustrate the principle.

Consider two graduate job packages presented in Table 2.7. A recent graduate is asked to choose among two graduate programs with respect to two criteria: starting salary and number of days of paid vacation. Both programs last for three years and they are essentially identical in all aspects except for vacation days. The total number of vacation days are equal in both packages (total vacation days = 45) but the distribution over the three years are different. In job package 1, the number of vacation days per year range from 5 to 25.In job package 2, the number of vacation days per year range from 20 to 10. Compare the two job packages, it seems likely that a difference of 20 vacation days in job package 1 will have a greater effect than a difference of 10 vacation days in job package 2 (bigger vacation range receive greater weight); but in fact, the total number of vacation days are the same for the two packages.

Table 2.7 Graduate program example to illustrate range sensitivity

Job package	Program	Starting salary	Vacation days
1	First year	$25,000	25
	Second year	$30,000	15
	Third year	$35,000	5
2	First year	$25,000	20
	Second year	$30,000	15
	Third year	$35,000	10

Goldstein (1990) and Fischer (1995) conducted experimental studies to test the range sensitivity of judgement. Goldstein (1990) found that when the criterion varied over a wide range, it had a greater impact on subjects' preference rankings than when it varied over a narrow range. Fischer (1995) suggested that '*the weight for each criterion is a scaling constant that reflects the impact of the range of levels of that criterion on the overall index of value*'.

Current practice

The review of the existing water strategies revealed that majority of the current practices in urban water management do not take in account range sensitivity and worst still, evaluation of the relative importance of the criteria are often made independent of the criteria range. This is one of most common mistakes in evaluating criteria importance. As summarised in Table 2.4 (column 3), nearly all long-term water strategies use a generic scoring scale (poor to good) to represent the range for the criteria (some for both qualitative and quantitative), without addressing the specific range for each criterion. It is often tempting for DMs to specify the relative importance of criteria on numerical scales without understanding the consequences (Keeney, 2002). Construction of a qualitative scale with linguistic labels requires a lot of effort such that appropriate values assigned (Dawis, 1987). However, the level of attention paid to the construction of the scale is generally low and which represent some of the difficulties accompanying many of the MCDA problems in urban water management. Most users are not aware of the pitfall associated with range sensitivity and thereby influencing the DMs' choice with arbitrary recommendations.

An example to illustrate this problem is given by Keeney (2002). Consider the importance of three factors in relation to the clean-up of hazardous waste sites. The three factors are: (1) economic costs of clean-up, (2) potential human life loss or sickness due to the hazard, and (3) potential damage to the environmental (i.e. flora and fauna). Majority of the responses ranked human life loss or sickness first and then environmental damage and then economic costs. Keeney raised the question about the fundamental value of a human life loss or environmental damage by asking the participants to rank the importance of spending \$3 billion, avoiding a mild two day illness to thirty people, or destroying ten square miles of mature, dense forest. The preferences changed when the trade-offs were conducted by measurable values. This shows that the elicited weights without reference to the criteria range only represent general values toward the criteria and not specific trade-offs among them. This also the case with most MCDA applications in water resources management (see MCDA applications review in Appendix C). Construction of a qualitative scale is one of the most popular approaches to standardise criteria scores as demonstrated through the journal article review (Figure 2.9). The performance of alternatives can be assessed by reference to linguistic labels. Similarly, direct assignment method is one of the most popular criteria weighting approach (Figure 2.8). The direct assignment method uses a pre-defined measuring scale (either quantitative or qualitative) to rate the importance of each criterion. The method of standardising criteria weights and assigning criteria weight with constructed scale is subject to range sensitivity if the criteria range is not specified.

2.6 Tools selection rationale to solve identified shortcomings

The following diagram (Figure 2.11) summarises the tools selected and the path leading to the selection (highlighted in colours) to address the three identified shortcomings associated with the use of MCDA. The theoretical treatment of these gaps or issues is well covered in the field of MCDA literature, the identification of these issues and application of the associated treatment in practice is limited. The current situation is that the theoretical developments have moved faster than empirical applications of MCDA (Ananda and Herath, 2009).

2.6.1 Double counting

The problem of double counting is associated with the problem structuring phase of decision making as discussed in Section 2.5.2 p.46. To avoid this problem, careful selection of criteria is required by examining the reasons why the criteria under consider are important to the decision making problem. Problem structuring methods (PSM) are a group of problem handling approaches which aim to assist DMs to identify and structure multiple criteria decision problems (Rosenhead, 1996). Most of these methods guide the users through a series of ideas generation activities to enable negotiations of a joint agenda, interactions between different groups of stakeholders, and to help create a sense of ownership of the problem.

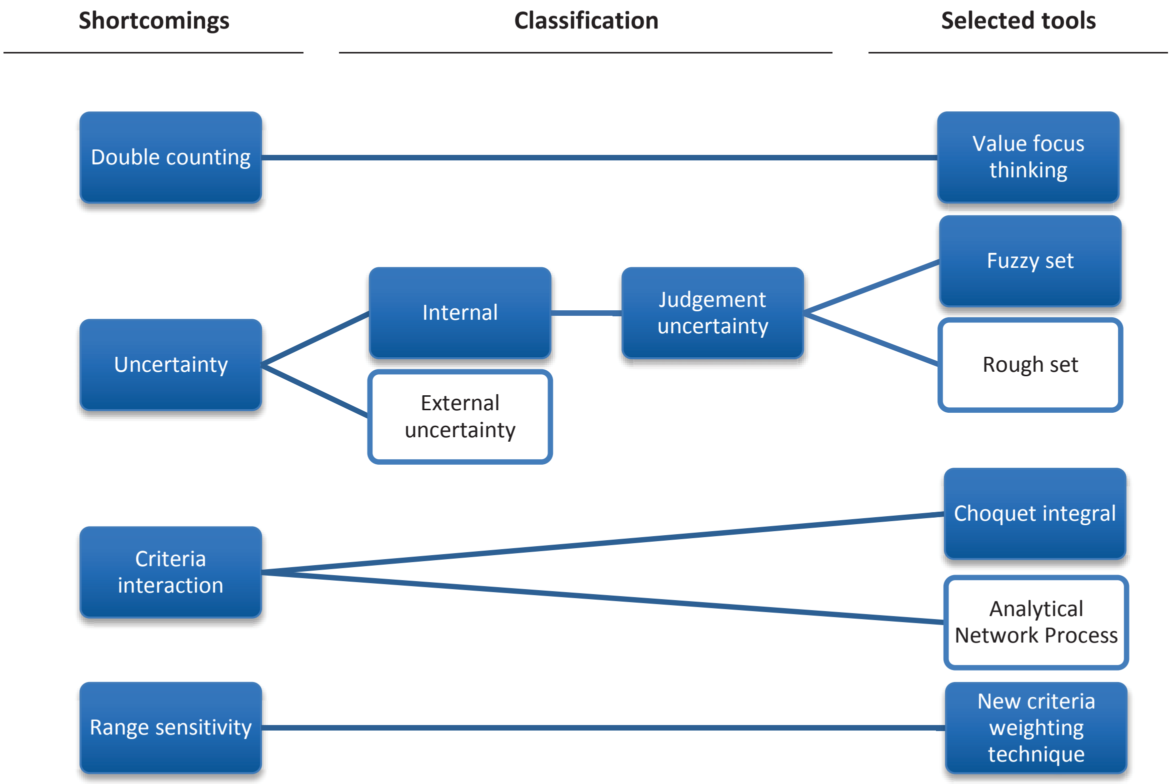


Figure 2.11 Summary of selected tools to address identified shortcomings

Some popular PSMs applied in decision analysis are (Mingers and Rosenhead, 2004):

- *Strategic options development and analysis* (SODA) developed by Eden and Fran (1989) – this problem identification method uses cognitive mapping as a modelling device to elicit individuals' preference. Cognitive mapping, also known as mind mapping is a form of representing individual 'construct systems', aimed to represent the problem as the DMs perceive it (Belton *et al.*, 1997).
- *Strategic Choice Approach* (SCA) developed by Friend and Hickling (2005) – is a planning approach centred on managing uncertainty (uncertainty about the environmental, guiding values and related decisions) in strategy situations.
- *Soft System Methodology* (SSM) developed by Checkland (1981) – is a general method of system redesign to assist DMs in building conceptual models to reflect the relevant world view. Conceptual models are not intended to represent what exists but to represent a stakeholder viewpoint in the form of linked diagrams.
- *Value focused thinking* developed by Keeney (1996) – evaluates alternatives by emphasising the importance of value instead of 'alternative-focused thinking'. Alternative-focused thinking focuses on eliciting DMs' value prior to identifying

alternatives. In contrast, preliminary alternatives are identified at an early stage in the decisions process and value focused thinking helps to generate and distinguish alternatives based on uncovering hidden values.

To deal with the problem of double counting, the PSMs generally adopted either one of the following approaches:

- *Differentiating criteria* – Keeney (1996) observed that the typical decision-analysis structuring process does not distinguish between fundamental criteria (criteria that are fundamentally important because they are valued by DMs) and mean-ends criteria (that are important because they have implications on fundamental criteria). Fundamental criteria should be discrete whereas mean-ends indicators would contain multiple attributes that are the essence of some fundamental criteria. Double counting occurs when means-ends criteria are incorporated into the criteria hierarchy to be used for evaluating alternatives. Value focused thinking and strategic options development and analysis (SODA) followed this approach to deal with double counting.
- *Splitting criteria* – splitting a single dimension into multiple criteria in order to obtain greater level of details pertaining to an objective. Redundancy can be identified in this way and the criteria are redefined to eliminate the double counted components (Roy, 1996). Strategic choice approach (SCA) and soft system methodology (SSM) followed this approach.

To illustrate the difference between the two approaches, an example is given in the following to contrast the two methods. In the Water Corporation's Water Forever plan (2008), the importance of land clearing was double counted in the two criteria, *physical footprint* and *capacity to enhance the environment*. The criterion physical footprint measured the yield per hectare of land cleared ($GL.yr^{-1}ha^{-1}$) and the other criterion measured the full spectrum of impacts on the environment, from enhancement to degradation. Impact on national parks, nature reserves, States forests, threatened ecological communities, wetlands and acid sulphate soils are accounted for in this criterion.

To determine which classification applies to the criteria (fundamental criteria or means-ends indicators), the reasons for each criterion are examined by examining why they are important:

- *Physical footprint* – this criterion was used as a surrogate for impact on biodiversity. This criterion was important because it revealed the magnitude of land clearing and its possible impact on the environment. Thus, affecting an option's capacity to enhance the environment. Hence, this criterion is a means-ends criterion. Furthermore, the yield component indicated the amount of resources extracted from the environment and together with the hectares of land cleared, this criterion showed the efficiency of production which can be translated to cost.
- *Capacity to enhance the environment* – this criterion was important because it is fundamentally important, correlating directly with one of the sustainability principles, the ability to conserve the environment. Hence this is a fundamental criterion.

The relationships between the fundamental criterion and means-ends indicator in this example are shown in Figure 2.12 (a). In the splitting criteria approach, the two criteria are split into more refined indicators and the common indicators between the two are 'land clearing in hectares' as shown in Figure 2.12 (b). According to Roy's (1996) suggestion, the criteria should be redefined to avoid the redundancy. In this case, either one of the two criteria (capacity to enhance the environment or physical footprint) has to eliminate the land clearing component. Although this can minimise non-redundancy, the splitting criteria approach does not show the relationship between these two criteria. Overweighting still occurs because these two criteria are treated as two separate entities instead of being one criterion. As a matter of fact, physical footprint should be a means-ends criterion to the criterion capacity to enhance the environment.

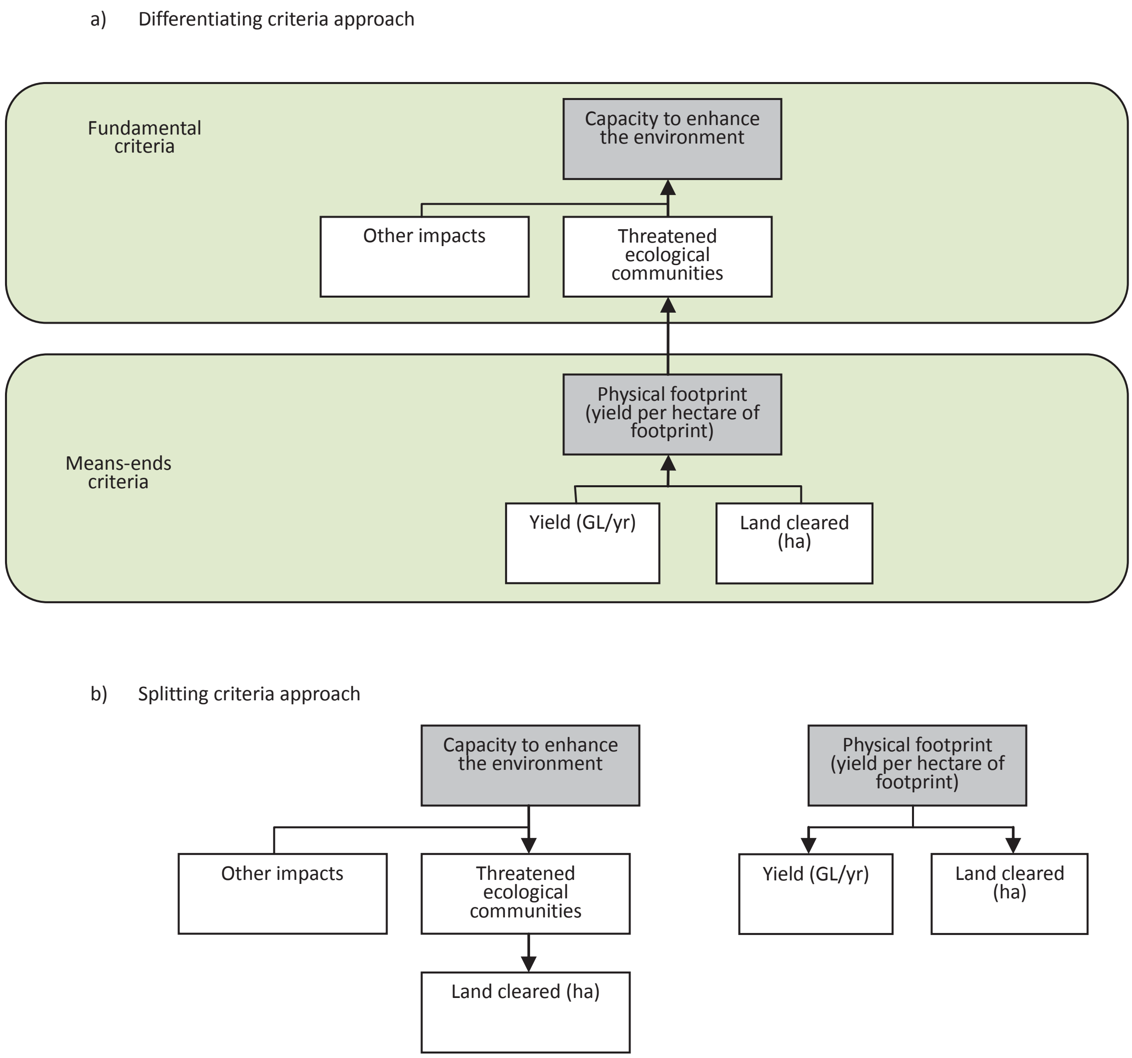


Figure 2.12 Examples of (a) 'differentiating criteria' and (b) 'splitting criteria' approaches

The problem with double counting was not demonstrated quantitatively in this thesis, because changing the value tree changes the analysed outcomes, regardless or not the criteria are double counted. The significance of eliminating double counted criteria is to make it easier for DMs to evaluate the criteria, as the criteria truly represent the DMs' value system. The only possible method to demonstrate the effectiveness of eliminating double counting is by conducting a series of workshops with a group of DMs to evaluate a decision problem with double counted criteria and another without double counted criteria. At the end of the workshops, the DMs were interviewed for the ease of evaluation with the two cases. This type of evaluation, however, is beyond the scope of this research given that this is a decision behavioural problem and requires cross disciplinary research work with social science.

<u>Justification for the selected tool: value focused thinking</u>

'Differentiating the criteria' was the selected approach to eliminate double counting, and thereby making value focused thinking the preferred PSM method. SODA followed the same procedure as value focused thinking to address criteria redundancy. Therefore, the latter was considered to be more valuable in providing fundamental guidance on this issue. The 'splitting criteria' approach was not selected for the following reasons:

- *Detail specification of a criterion can lead to overweighting* – DMs are biased to overweight parts of a value tree that are developed in detail relative to those that are not. Webb *et al.* (1988) demonstrated this behavioural influence on weight assignment through an experimental research in comparing different structures of the value tree. It was found the method of splitting the criteria into greater detail as a mean to avoid double counting can indirectly over emphasis that component of the value tree.
- *Fundamental value tree* – proxy criteria (indicators that are chosen as proxy to measure the criteria in the absence of a natural measuring scale) can be confused with the fundamental criteria. Splitting the criteria is aimed at expanding the criteria to a basic level and proxy criteria are often used to represent the criteria at a basic level. DMs are prone to evaluate these proxy criteria simply because they appear on the value tree. Splitting the criteria does not make such a differentiation (fundamental and means-ends criteria) and this could lead to biased evaluation.

2.6.2 Judgement uncertainty

To deal with the problem of judgement uncertainty, there are three identified tools that can be used to model the imprecision in linguistic judgement: probability theory, rough set theory and fuzzy set theory. These three methods are described briefly to provide the basis for the justification of the selection.

Probability theory

Decision analysis is filled with different forms of uncertainties as discussed in Section 2.5.3 p.48. It becomes necessary to explore the effect of inevitable uncertainties on the selection of alternatives. A class of analytical procedures collectively referred to as sensitivity analysis is commonly carried out to understand the relationships between changes in the input values and subsequent changes to the ranking of alternatives (Evans, 1984). Sensitivity analysis is used to determine the stability of the ranking of alternative with respect to the uncertainties in the concerned variables. One common method is to describe the uncertainties of the variables using a probability distribution and observe the effect of variance on the output distribution (Frey and Patil, 2002). Different input variables are varied one at a time to observe the changes in the output.

Probability theory has its root in analysing games of chance, which is founded on random processes that arise out of chance (Kallenberg, 1997). These chances represent frequencies of occurrence that can be measured by probability distributions. Problems such as tossing a coin, rolling a dice and picking coloured balls out of a hat are examples of stationary random processes. This approach to uncertainty involves the notion that the event of a future can be characterised probabilistically (Lindley, 1987).

Rough set theory

The theory of *rough* sets was introduced by Pawlak (1982) to express vagueness by employing a boundary region of a set. The conventional definition of a set (*crisp* set) requires that all mathematical notions of a set must be exact. A crisp set consists of all elements that can be classified uniquely to the set or its complement. A rough set, in contrast, refers to a set of objects that can only be classified with uncertainty as members of the set or of its complement. To define vague information, rough set theory uses two concepts: the lower and the upper approximation of the vague information. The lower approximation consists of all objects that belong to the set that describe the vague value and the upper approximation consists of all objects that possibly belong to the vague set. The difference between the lower and the upper approximation constitutes the boundary region of the vague value. A crisp set does not have any boundary region but a rough set has a boundary region. A nonempty boundary region of a set means that our knowledge about the set is not sufficient to define the set precisely (Pawlak, 1991). As a decision support tool, rough set theory offers techniques to generate minimal sets of data (i.e. decision rules) or find patterns in data based on specification of the decision (Pawlak, 1997).

Fuzzy set

Fuzzy set theory, developed by Zadeh (1965), is the very first successful approach to model vagueness in human understanding. Fuzzy set theory defines the concept of vagueness differently from rough set theory, in which vagueness or fuzziness refers to the lack of distinction between sets of elements and their complements. Central to fuzzy set theory is the concept of *fuzzy* set which is a set that contains elements having varying degree of membership between 0 to 1 in the assertion that the elements belong to the set. A membership function is one that measures the degree an object belongs to a set by its membership (the concept of membership function is described in further detail in Chapter 4). An example is the fuzziness in our natural language which lacks sharpness in its information conveyed.

Justification for the selected tool: fuzzy set theory

Fuzzy set theory was the adopted approach to model judgement uncertainty. Further detailed information on fuzzy set theory is presented in Appendix D. The following list the reasons for selection:

- *Suitable for modelling internal uncertainty* – Uncertainty is multi-dimensional and probability theory allows only one of its dimensions to be captured (Klir, 1989). Zadeh (1983) argued that the conventional approaches to the management of uncertainty was inadequate to deal with all aspects of uncertainty. As discussed earlier in Section 2.5.3 p.48, uncertainty can be classified as either external or internal uncertainty. Not all types of uncertainties are suitable to be described as random processes. Internal uncertainties such as ambiguity and imprecision do not arise because of random processes. Although it is possible to model these forms of uncertainty with random processes the results may not be reliable (Ross, 2004).
- *Define imprecision* – Rough set theory and fuzzy set theory appear to be competing methods to model vague information, but their aims are to achieve different purposes (Dubois and Prade, 1990). The key difference is that a rough set is concerned about distinguishing between objects in a set, while a fuzzy set model is concerned with the ill-definition of a set. A rough set operates by elimination of data outside the set, whilst a fuzzy set defines the impreciseness of the vague information.

With this perspective, a fuzzy set approach is more useful in this research because the author aimed to define the imprecision in qualitative linguistic assessment terms in this research and not to eliminate imprecision.

- *Well tested and accepted method in the field of water resources management* – Fuzzy set theory is one of the most popular approaches used in conjunction with MCDA for water resource planning and management (Hajkowicz and Collins, 2007). Some examples of fuzzy MCDA techniques that were used in water resource management are fuzzy analytical hierarchy process (Srdjevic and Medeiros, 2007), fuzzy compromise programming (Bender and Simonovic, 2000) and fuzzy multi-objective programming (Nayak and Panda, 2001).

2.6.3 Criteria interaction

To deal with the problem of criteria interaction there are two main approaches, analytical network process and fuzzy measures.

Analytical Network Process

Saaty (Saaty, 1996; 2004a) developed analytical network process (ANP) as a generalisation of Analytical Hierarchy Process (AHP). ANP deals with dependency between criteria in decision making problems. In ANP, the decision problem value tree is not structured as a top-to-bottom form of a hierarchy. Rather, the basic structure of ANP is an influence network of clusters and nodes contained within the clusters. The network allows feedback loops that connect a component to itself to allow feedback. The component can be either a source node (original of path) or a sink node (destination of path). In this way, the importance of an alternative is allowed to influence the importance of criteria. The challenge is to determine the priorities of the elements in the network. Although priorities are determined the same way they are in the AHP using pairwise comparisons and the 1–9 point scale, it is more demanding because the feedback network involves cycles and it can be an infinite process.

Fuzzy measures

Fuzzy capacities were first introduced by Choquet (1953). The concept of capacities was later defined as a measure by Sugeno (1974) and this gave birth to a new function called the *fuzzy measure*[6]. Fuzzy measure is a particular aggregation function which

[6] It should be noted that fuzzy measure has nothing to do with fuzzy set.

aggregates a group of criteria with interaction. It is a set function $\mu(N)$ in which $N := \{1, \ldots, n\}$ is the index set of criteria *c*, satisfying the following axioms:

(i) $\mu(\emptyset) = 1, \mu(N) = 1$

(ii) $\mu(A) \leq \mu(B)$ whenever A⊂B

Suppose a group of criteria A, ($A \subseteq N$), called a coalition has interaction between some of the criteria within the set (i.e. positive or negative synergy between some criteria), the fuzzy measure of A, $\mu(A)$ gives the importance or weight of the coalition A in order to represent the complex interaction phenomena between criteria. Choquet integral is a family of aggregation functions defined with respect to a fuzzy measure or capacity (Grabisch, 1996). The main difference between fuzzy measures and the other forms of aggregation is that it takes into account not only the importance of the criteria and the ordered position of the criteria, but also the interaction between criteria. Further detail on the Choquet integral is presented in Appendix D2.

Justification for the selected tool: Choquet integral

The fuzzy measure, Choquet integral was selected as the tool to deal with criteria interaction for the following reasons:

- *Uses holistic instead of decomposed weighting method* – The decomposed weighting procedure takes one criterion or a pair of criteria at a time when making weight judgements (e.g. pairwise comparison). Holistic weighting procedure requires that DMs consider several criteria at a time (e.g. trade-off, direct assignment) (Weber and Borcherding, 1993). Hogarth (1980) noted DMs may be prone to see relationships between criteria where none exists because people are found to be over-confident in judgement. This is the case especially when there are too many pairwise comparisons to be made which create high cognitive loading for the DMs. ANP uses only pairwise comparison to determine criteria weights based on DMs interpretation of criteria performance scores. In contrast, Choquet integral has the flexibility to adopt either a holistic or decomposed weighting procedure.
- *Strong mathematical model* – Fuzzy measure has its root in the capacity theory, a well-established mathematical theory in functional analysis (Murofushi and Sugeno, 1991). Choquet integral has practical application in many areas (Rowley *et al.*, under review; Grabisch and Labreuche, 2008).

2.6.4 Range sensitivity

Fischer (1995) stated in the range sensitivity principle that:

> If a criteria score is normalised locally then criteria weights should vary as a function of the range of criteria values in the local context. If a criterion value function is normalised globally, then the criteria weight should be fixed and independent of the range of attribute values in the local context.

The local and global context mentioned in Fischer's range sensitivity principle refers to the reference points of the criteria range. *Reference points* are the two end points of the measurement scale for the criteria indicating the upper and lower bound of the measurement range. Selection of reference points is an important step to define the criteria range. There are two types of approach to determine the reference points according to Goldstein (1990):

- *Local scale* – the reference points are defined according to the highest and lowest scores achieved by the alternatives for each criterion. The other alternatives will receive intermediate scores bounded by these two end points. This approach provides a good starting point to get a rough idea of the measurement scale. The criteria weights assigned in a local context are more prone to inconsistency in weighting because DMs do not adjust properly for changes of ranges (Weber and Borcherding, 1993).
- *Global scale* – the reference points are defined with respect to the wider set of possibilities. The two reference points can be defined according to the ideal highest and lowest points for each criterion. Although, it is takes more effort to identify the global reference points, this approach has the benefit of having a more general scale than a local scale.

To illustrate the difference between the two types of scale more clearly, an example from Belton and Stewart (2005) is presented here. Suppose the number of direct flights per week to Washington DC on the preferred airlines is used to represent level of accessibility for an office relocation decision problem. The number of flights vary from 2 (for Warsaw and Milan) to 15 (for Amsterdam and London). A local scale could then be constructed to indicate the values of the criterion flights per week, with $v_i(2) = 0$, and $v_i(15) = 100$. This local scale could be acceptable if no other cities were considered. If the DMs wished to consider other cities for which the numbers of lights fall outside of this range, then this local scale would not be satisfactory. To set up a global scale, the minimum possible number of flights is 0. At the other extreme, perhaps it has been established that there is unlikely to be any city having more than 4 flights per day on the preferred airlines, so the effective maximum flights per week is 28. A global scale is constructed in such a way that $v_i(0) = 0$, and $v_i(28) = 100$.

According to Fischer's range sensitivity principle, criteria scores should be standardised with respect to the global scale. There are no specific tools to address this issue, as such, the author developed a new criteria weighting technique and criteria score standardisation based on the concept of mitigation. The details are presented in Section 4.2 p.122.

2.7 Conclusions drawn from the literature review

Sustainable urban water management requires well-informed decision making based on holistic assessment of the selected criteria. This in turn requires an integrative approach to link the various aspects that constitute sustainability. Four different integrative approaches are reviewed and compared including: CBA, TBL, IA and MCA. Through the comparison, MCDA, an extension of MCA appeared to be a suitable candidate as an integrative approach for sustainability assessment. It was selected as the preferred integrative approach because of its capacity as an aid to decision making by incorporating stakeholder participation. Also MCDA serves as a useful means of communication between DMs because it provides a structural approach to assist DMs to explore and understand their own values.

An overview of MCDA in sustainability assessment for urban water management was presented. MCDA, an integrative approach with an orientation to aid decisions, is a rapidly evolving field. The application of MCDA in sustainability assessment has the potential to help shift urban water management towards a more sustainable level. However, despite the fact that MCDA has been widely applied in water management, there are still a number of shortcomings with MCDA that need to be addressed. Through an extensive review of MCDA applications in water resources management, four shortcomings associated with the MCDA methods (double counting, judgement uncertainty, criteria interaction and range sensitivity) were identified. The theoretical treatment of these issues is well covered in the field of MCDA literature, but the management of these issues is not adequate. These shortcomings formed the basis for research in this study because of the potential to improve the overall quality of decision making.

Different tools to address each of the four shortcomings were reviewed. The findings are briefly summarised as follows:

- *Double counting in problem structuring* – There are no hard and fast guidelines as to how the problem of double counting should be assessed or handled. Value focused thinking provides a general direction by differentiating between the types of criteria.
- *Judgement uncertainty* – Uncertainty is a multi-dimensional issue which cannot be captured solely by probability theory. Imprecision in value judgement is a form of internal uncertainty that is best modelled by fuzzy set theory.
- *Criteria interaction* – The problem of criteria interaction is studied in depth in game theory and a special form of mathematical model, fuzzy measure is developed to deal with such an issue.
- *Range sensitivity* – A new criteria weighting technique and criteria score standardisation based on the concept of mitigation was developed as part of this research.

3 Methods and Materials

3.1 Introduction

The previous chapter identified four shortcomings associated with the use of MCDA: (1) double counting, (2) judgement uncertainty, (3) criteria interaction and (4) range sensitivity. The selection of tools to address these four shortcomings and the associated rationale are given in Section 2.6. A decision support approach was developed as part of this research that utilised the selected tools to address the four shortcomings. The decision support approach consists of three stages 1) problem structuring, 2) preference elicitation and modelling and 3) aggregation. An overview of the decision support approach is first given in Section 3.2.

To test-proof this approach, an urban water decision case study was used. The design of the case study is described in Section 3.3, addressing the issues of sample selection, data requirement and design of research method. This is followed by a detailed description of the workbook design, pilot test, main study and analysis. This chapter focuses on the first stage of the decision support approach and the selected case study, Gold Coast Water Future (GCWF) is presented in Section 3.4 to illustrate the first stage. Details of the GCWF case study, including the decision problem, the decisions making process involved and the multi-criteria approached adopted are presented. The structure of Chapter is illustrated in Figure 3.1.

3.2 Decision support approach

This section outlines the structure of the decision support approach. There are three stages in the decision support approach which is in line with the generic process of a MCDA method (Figure 2.4). However, this framework only includes the first three stages of generic MCDA process because it is beyond the scope of this research to include recommendation (Figure 3.2). Recommendation is the last phase of a MCDA process which generally involves arriving at one preferred alternative, ideally agreed by all the stakeholders.

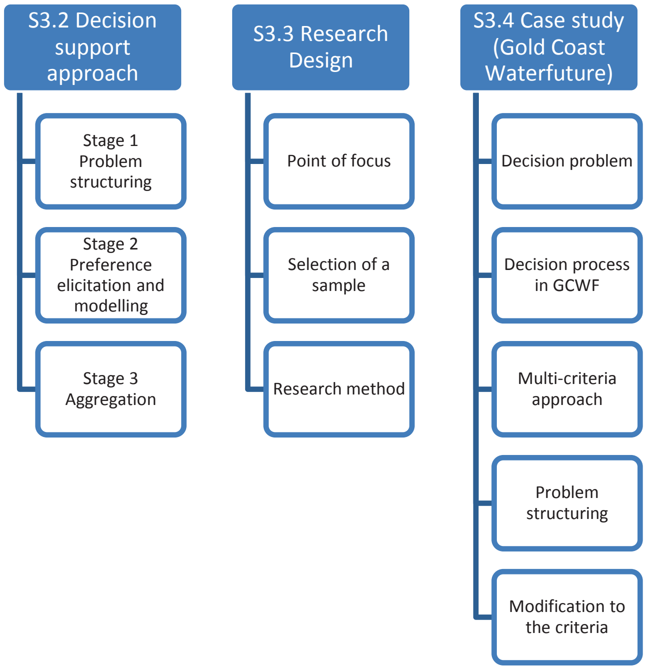


Figure 3.1 Structure of Chapter 3

Outputs from MCDA methods only provide suggestive order preference of alternatives consistent with the DMs' point of view. The outputs provided by the MCDA methods are there to support DMs' decisions but DMs are not limited to choice computed by MCDA. This is the reason why the author stresses on the 'aiding' component of MCDA and not on the 'making' component of MCDA.

3.2.1 Stage 1. Problem structuring

This stage addresses double counting. The problem with double counting, as discussed in Section 2.5.2 p.46, occurs as a result of poor criteria selection in the problem structuring phase. For the double counting issue, the author proposed the use of the Value Focused Thinking method to evaluate the reasons for the selection of each criterion. The rationale for using Value Focused Thinking is discussed in Section 2.6.10 p.63. To illustrate the process, the procedure was applied to the GCWF case study to highlight the specific instances of double counting (instances of criteria interaction were also identified but the issue is not addressed until stage 2). A new set of criteria was developed to eliminate the double counting identified. The application of this process is described in Section 3.4.4 p.100.

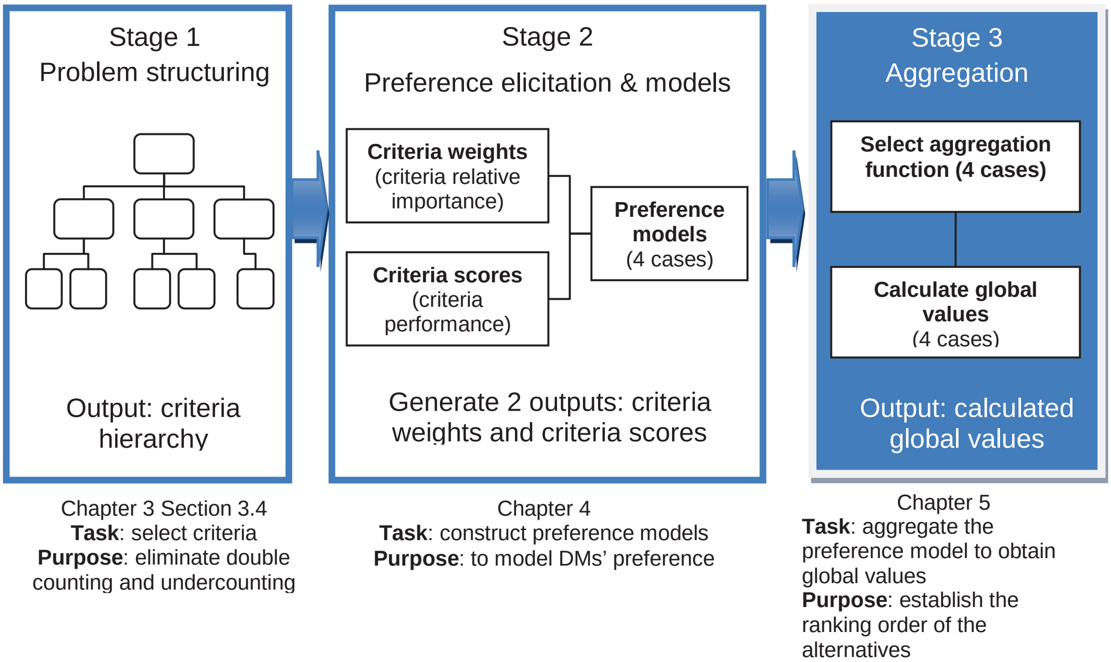


Figure 3.2 Structure of the developed decision support approach

3.2.2 Stage 2. Preference elicitation and preference models

The purpose of stage 2 is to identify relative criteria importance and the performance rating of the criteria which are conveniently referred to as: (1) criteria weights and (2) criteria scores. There are two components in stage 2, preference elicitation and preference modelling (see Chapter 4). The first component preference elicitation is concerned with eliciting preferential judgement from the DMs about the criteria weights and criteria scores. The second component preference modelling is concerned with constructing a model to represent DM's preferences. These preference models are based on the selected underlying aggregation model to combine the criteria weights and criteria scores. A special feature of MCDA is that the selected aggregation model directly dictates the form of criteria weights and criteria performance scores to be elicited. In other words, the input data required for the decision model is critically related to the decision support methodology (DSM) selected.

In this research, four preference models were constructed which adopted different types of aggregation models and forms of criteria weights/criteria scores. These four preference models were constructed such that each model addressed different combinations of the identified shortcomings, judgement uncertainty and criteria interaction. One of the four preference models was a base case scenario which adopted the conventional simple additive weighting approach. This method serves as a base case to which the other three cases were compared.

3.2.3 Stage 3. Aggregation

The preference models constructed in stage 2 are aggregated in this stage. The purpose of aggregating the preference models was to associate a value to each alternative in order to establish a preference order for them. This value is referred to as the *global value*. The global values permit an order of preference to be established between the alternatives. Each of the four preference models adopted different aggregation functions corresponding to its assumptions in relation to the shortcomings. The process of aggregation and the calculated global values are presented in Chapter 5.

3.3 Research design

A properly framed research design can have a fundamental impact on the results obtained thereafter, thus affecting the outcomes of research finding. In order to design the research properly, the following factors were taken into consideration:

- *points of focus* – identify study problem, the data requirement
- *selection of a sample* – identify the relevant people to study and to collect data
- *research method* – design the method and procedure to collect data

3.3.1 Point of focus (what to study)

The focus of the study was to test-proof the decision support approach. To fulfil this, the task was to design a research program for applying the decision support approach. More specifically, the point of focus was to *design an experiment to find out how well the applied decision support approach modelled the DMs' preferences*. The following describes the experiment in relation to the three stages of the decision support approach.

Stage 1. Problem structuring

The stage served as a preparatory step for the other two stages, by producing a hierarchy of criteria as input for stage 2 and stage 3 that were non-redundant and identify any interacting criteria.

Stage 2. Preference elicitation and modelling

The decision support approach involved consideration for judgement uncertainty and criteria interaction, as such, these two shortcomings were accounted for in different preference models. Four cases of preference models were developed including a base case representing the scenario without the influence of these shortcomings. These four cases of preference models are described as follows:

Case 1: Assume without judgement uncertainty and criteria interaction – different aggregation operators in the value measurement theory was applied to obtain aggregated results. The aggregated results using this method considered no criteria interaction and judgement uncertainty.

Case 2: Assume with judgement uncertainty – a fuzzy simple additive weighting method was applied to account for judgement uncertainty.

Case 3: Assume with criteria interaction – the Choquet integral was applied to account for criteria interaction.

Case 4: Assume with judgement uncertainty and criteria interaction – the Choquet integral was applied in conjunction with fuzzy sets to account for both judgement uncertainty and criteria interaction.

These four cases are dispersed throughout Chapter 3, 4 and 5. To help reader to follow the applications of the four cases to the case study, a diagram is provided for this purpose as illustrated in Figure 3.3.

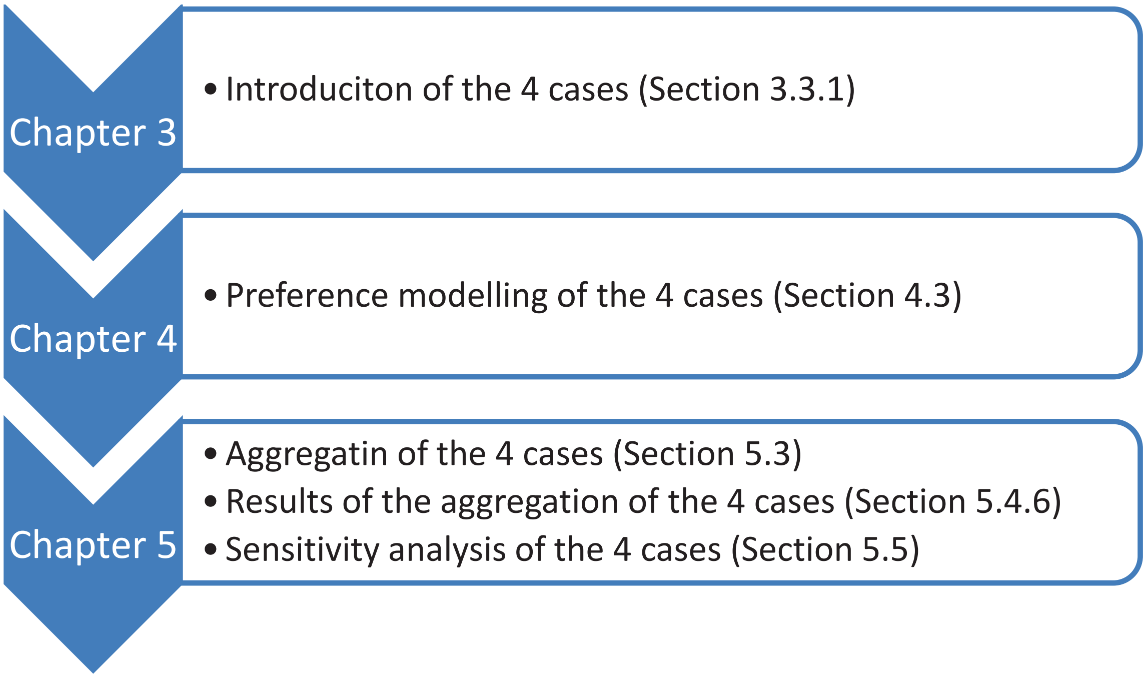


Figure 3.3 Applications of the four cases to the case study

Stage 3. Aggregation

The desired outcome was to find out which preference model was able to model the DMs' preference more closely. By examining the differences in the four preference models' ability to model DMs' preference, it was made possible to investigate the relative influence of judgement uncertainty and criteria interaction on the analysed decision results. To make the comparison, two types of outputs are generated from the experiments.

- *Observed global value* – the overall value associated with an alternative which was the study subjects' rating of the alternatives without using any decision support tools. The participants were asked to give an overall score for each section after they worked through the exercise, to ensure that they understood the problem. The idea was to treat the observed global values as the optimum or ideal sets of goals, in order to have sets of fixed points to examine the uncertainty associated with the judgment. A similar study performed by Zimmermann and Zysno (1980) provides the theoretical justification for such an undertaking.
- *Calculated global value* – the overall value associated with an alternative which was obtained from the aggregation of the four preference models.

The calculated global values for the four cases were compared with the observed global values. The comparison between the calculated and observed global values was used to investigate the influence of the shortcomings by using correlation analysis. It was by no mean that the observed global values were implied as the absolute truth. Like all judgement, the observed global values were also subject to changes under new information or change of value. For the sake of understanding the judgment uncertainty and criteria interaction associated with the judgment (i.e. observed global values), it was necessary to fix the observed global values as the optimum judgment. The significance of the comparisons was in the ability to reflect the influence of judgement uncertainty and criteria interaction on the final ordered preference for the alternatives.

To generate the calculated and observed global values, three types of data were collected in the experiment:

- *Performance data for all criteria* – provides the basic information on which the study subjects to base their judgements on. This type of data was collected through desktop study (e.g. a set of criteria and criteria performance scores).
- *Perceived criteria importance from the study subjects* – the study subjects' judgements on the importance of a set of criteria based on their own individual preferences. This type of data was collected during the main study (e.g. criteria weights).
- *Empirical aggregated results from the study subjects* – the study subjects' judgements on a set of options without using any decision support analysis. This type of data was collected during the main study (e.g. observed global values in the form of ranking or rating of the alternatives).

These three data types produced the observed and calculated global values to allow for comparisons between the two in the analysis. The relationships between the three types of data are illustrated in Figure 3.4.

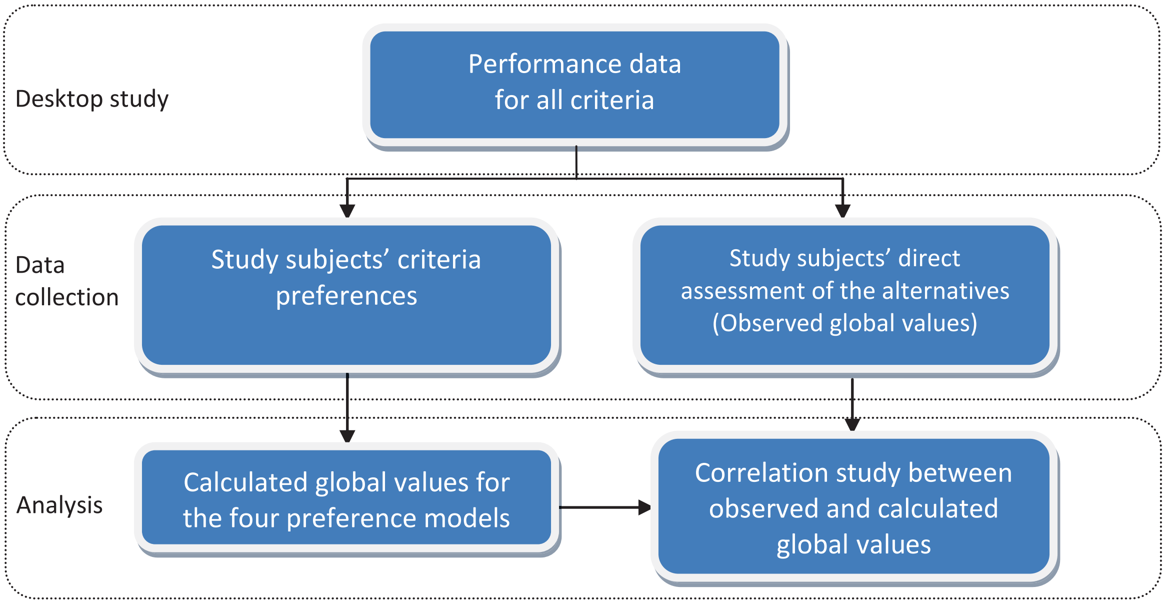


Figure 3.4 Relationships between the data requirements for the study

3.3.2 Selection of a sample (who to study)

The point of focus highlights the data required for the research and two of the data types listed are acquired from study subjects. The selection of a sample is about finding a suitable sample to participate in the study. A sample is a collection of elements considered for selection as the subjects in a research study (Babbie, 2007). A sample can range from individuals, groups to organisations. For example, a sample can be a class of undergraduate students studying environmental engineering. This section addresses issues in regards to the selection of a sample for a research study.

With this perspective in hindsight, a sample was determined by the following steps:

- Identify study population
- Select sampling technique
- Select sample.

Identify study population

Firstly, a study population was identified. A study population refers to a group of elements in which a study aims to find more about and from which a sample is actually drawn from. Ideally, the study population should be all real DMs in the urban water industry in Australia and the research period should carry over for a period of time for the participants to be familiar with the decision problem. However, it was not a simple task to fulfil these requirements realistically. The topic of urban water management was a sensitive issue at the time during which this research was carried out as the water industry was going through a phase of long-term planning. There were limitations as to how much a water decision makers could comment on the issues, which increased their reluctance to participate in the study. Furthermore, longitudinal research which required multiple meetings with the subjects was not particularly feasible without a strong incentive or interest from the participants. Time constraint with the water managers was also an issue. Therefore, the target research sample was broadened out into three groups. The first two study population groups were selected to balance the anticipated low involvement from water managers in the study:

- water users
- water experts
- water managers.

A basic criterion for the selection of a study population was that they must have adequate understanding of urban water management. Therefore, the water user group was recruited from postgraduate/final year undergraduate students studying environmental management at the University of New South Wales (UNSW) School of Civil and Environmental Engineering. For the water expert group, academic/research staff specialised in water engineering from UNSW were recruited. For the third group managers from the water industry in Sydney who were involved in the planning of Sydney's Water Metropolitan Plan were recruited.

<u>Select sampling technique</u>

The second step was to identify a sampling technique. There are two basic groups of sampling techniques, which are listed below (Bouma, 2000).

Random sampling

This method involves the identification of not only the study population, but also each and every single element within the population (i.e. identify all water managers in the water industry in Sydney, all students who studied environmental engineering and all research/academic staff in UNSW). After each individual is identified, a method of selection is devised to randomly select individuals which ensure that each individual has the same probability of selection.

Non-random sampling

Non-random sampling is conducted in situations in which there is no list of all elements in the study population. There are four different types of techniques under this group: reliance on available subjects, purposive sampling, snowball sampling, and quota sampling.

Reliance on available subjects: This technique utilises whatever is immediately available such as postgraduate students and academics from the same institution as the author. The advantage is that these people were more available for the study but the disadvantage is that the findings are limited to the people immediately available.

Purposive sampling: This method relies on the researcher's knowledge of a population and its elements, in order to select a sample that best matches the aim of the study. For example, the author could obtain contacts in the water industry through supervisors.

Snowball sampling: This procedure is appropriate when the members of a population are difficult to identify. This involves the identification of a few target members, and then asks those individuals to provide further information to locate other members of that population. A snowball effect will take place as each located subject introduces other subjects.

Quota sampling: A quota can be set to ensure the sample studied meets all criteria. By fulfilling a quota, it is ensured that the group in the sample for analysis are adequately represented.

Random sampling produces the most accurate results that are representative of the population. However, it is not often possible to satisfy all requirements of simple random sampling (i.e. each individual has the same probability of selection). The process can also become tremendously complex because all individuals have to be identified in the population. The practicality of implementing this method is low and therefore this sampling method was not selected. In comparison, the practicality of implementing non-random sampling is higher. The reason is that the process of identifying suitable samples is simplified without identifying all elements in the population. A combination of the four techniques described in non-random sampling was adopted.

Reliance on available subjects: Two main groups of available subjects were postgraduate students studying environmental engineering and academic staff at the same school as the author. The postgraduate students represented the water user group as they had sufficient understanding of the urban water management system but not to the extent as water experts. The second group, academic staff represented the water experts.

Purposive sampling: In this research, the author had personal contacts with some of the academic staff at UNSW. The author had knowledge of which academic staff were specialised in the field of urban water management, and hence these academics were targeted for participation in the study.

Snowball sampling: In this research, members from the water manager group were the most difficult to identify. Information on a few members was first identified through the contacts of the academic staff at UNSW. The identified members invited other new members in their work group to participate in the study.

Quota sampling: In this research, a minimum quota was set to be twenty. This quota was selected to match at least the twenty Advisory Committee members in the selected case study (see Section 3.3.30 p.88 for rationale for sample size).

Invite samples

Different techniques were adopted to invite samples from the three study populations:

- *water users* – verbal invitations were extended to three postgraduate classes in environmental management over the course of a year (semester 2 in 2009 and semester 1 in 2010)

- *water experts* – email invitations were first sent to identified members with follow-up verbal invitations
- *water managers* – email invitations were first sent to identify members and subsequently, the located members sent emails to their working group to extend the invites.

3.3.3 Research method (how to study)

To obtain the three types of data required, there were three possible methods: observe a field study, utilise a completed case study and review documents. The three methods are described in Table 3.1 with the associated reasons for selection or non-selection. The method of case study was chosen. Figure 3.5 shows a flow chart of research activities.

Selection of case study

A desktop study was conducted to examine a range of published long-term water strategies. A review of the long-term water strategies is presented in Table 2.4. The following criteria were considered when selecting an appropriate case study:

- *an existing and completed urban water strategy* – it was important that the water strategy was endorsed by the respective water authorities and it would not be sensitive to carry out any further analysis.
- *detailed performance scores for all criteria* – well documented performances scores was important so that sufficient information could be provided to the study subject during the interview.
- *followed a multi-criteria decision framework* – a criteria hierarchy would be constructed if a MCDA framework was followed. The problem with double counting could be identified with greater ease.

Table 3.1 Comparison of research methods

Method	Description	Pros	Cons
Field study (prospective)	Observe a real decision making problem in the context of water management planning and collect data from the actual decision makers.	This would be the ideal method to conduct this research as the decision problem is real and the DMs are keen to participate in the decision problem.	This might be sensitive to the decision makers at the time when decision was being made. Data were also not readily available for confidentiality reasons. The author approached a water authority at the time when they were in the decision making process about conducting such a study. The proposal was rejected for the reason above.
Case study (retrospective) (method chosen)	Use a completed urban water management decision making problem and collect data from a group of study subjects with understanding of urban water management.	The benefits include availability of performance data for criteria which would have been more difficult to obtain if it was in a field study scenario.	Drawbacks for using an existing case study with a group of study subjects are discussed in detail in Chapter 6: discussion and conclusion.
Review documents	Obtain data from relevant literature.	This would require the least amount of interactive research work with real participants.	There were no available data for a similar type of study in the context of urban water management through literature research.

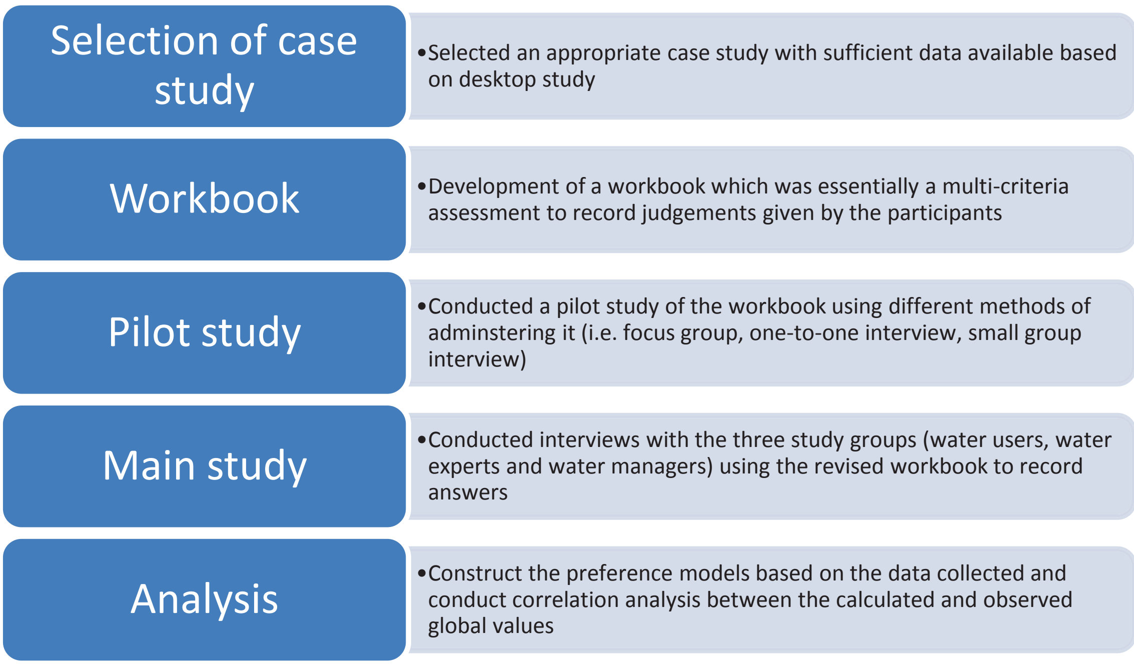


Figure 3.5 Flow chart of research activities

Five water strategies were reviewed with respect to the three selection criteria stated above. The comparisons are summarised in Table 3.2. After reviewing the five water strategy plans, the Gold Coast Waterfuture (GCWF) (2005) project was selected as a case study. This project was the only one that satisfied all three criteria. It followed a multi-criteria approach, which was well documented with detailed analysis. Furthermore, the GCWF is an important example of a successful water planning project. This is evident through the accreditation of Global Water Awards 2009 and the 2009 Australian Water Association Queensland and National Water Environment Merit Award for Gold Coast Water's contribution to sustainable water management through GCWF.

Table 3.2 Assessment of different water strategies with respect to the selection criteria

Water strategy	Existing and completed case study	Well documented performance data	Follow a MCDA framework
Goulburn Valley Water GVW2055 (Goulburn Valley Water, 2007)	Yes	No	Yes
Gold Coast Waterfuture (Gold Coast Water, 2005)	Yes	Yes	Yes
Water Forever (Water Corporation, 2008)	No	No	Yes
Water for Good (Government of South Australia, 2009)	No	No	No – a cost benefit analysis approach was adopted
WaterPlan 2050 (Gosford-Wyong Council's Water Authority, 2006)	No	Yes	Yes

Range of methods

Three ways were considered for obtaining the three data types as outlined in Section 3.3.1 p.74.

1. Survey: This involves a structured list of questions presented to study subjects which can be answered privately. This method has the potential to survey a large number of study subjects economically, but the data quality may be lower than some other methods because the study subjects may not have an adequate understanding of the issues in urban water management. Furthermore, if there are any queries in relation to the question, they cannot be addressed immediately. On the positive side, an advantage is that the survey reduces any potential influence from the researcher's opinions because the participants have to complete the survey on their own without interaction with the researcher.

2. Interview: An interview involves face to face discussion with an individual study subject who responds orally to questions on a topic. The process of interview is highly structured and responses from the participant can be recorded in the form of a workbook. However, bias can be introduced by the researcher's opinions as there is a high level of interaction between the study subjects and the researcher.

3. Focus group: A focus group involves asking questions of study subjects in an interactive group setting. The study subjects can freely discuss the results with one another and this can produce data and insights that would be less accessible without interaction in a group. Another advantage is that more study subjects can be involved at a single time compared to individual interview. The question remains, what is the size of the focus group to allow for qualitative discussion between study subjects?

The methods of individual interview and focus group were both selected for trial in the pilot test because these two methods could guarantee the quality of data and ensured that the study subjects responded to all questions. A survey was not selected because there was no quality control in a survey as the researcher could not interact with the study subjects. For example, if the participants misunderstood a question or fail to answer all the questions, the research could not correct them to ensure the quality of the responses were good.

Workbook

To record responses from the study subjects during interviews and focus groups, workbooks were used. The workbook was essentially a multi-criteria assessment to obtain the value of any trade-offs from each individual study subject. The workbook was divided into five sections covering five criteria categories specific to the GCWF project. These five criteria categories covered the different aspects of sustainability: (1) social, (2) ecosystem (a subset of environment), (3) environment, (4) technical and (5) overall (included economic). More details on the five criteria categories are discussed in

Section 3.4.5 p.109. For double counting, judgement uncertainty and range sensitivity, all sections applied but for criteria interaction, only the ecosystem and technical sections applied. In these two sections (ecosystem and technical), extra data were collected for applying the Choquet integral to model criteria interaction.

Each section addressed criteria related to its own categories and had three tasks:

- *Criteria preference*: rank the criteria based on their importance
- *Criteria preference*: quantify criteria importance
- *Alternatives preference*: rank or quantify the preference for alternatives.

For the ecosystem and technical sections, there were two extra tasks for obtaining more data to model criteria interaction:

- Preference for pairs of criteria: rank the criteria pairs according to their importance
- Define the strength of preference in between the criteria pairs.

Pilot study

The workbook was pilot-tested in different settings (such as small group interview or large focus group) to find out which method was more appropriate for administering it (Table 3.3). Another purpose was to test the workbook. This phase of the research is referred to as the pilot study. A copy of the pilot workbook is attached in Appendix E3.

There were five pilot tests carried out with different study groups and group settings to test the different combinations. In total, 4 water experts and 39 water users were involved (n = 43) in the following pilot test settings (refer to Table 3.4):

1. *individual interview* was carried out with one water expert
2. *small group interview* was carried with two water experts
3. *small focus group with mixed stakeholder group* was carried out with a mixture of different stakeholder groups, one water expert and three water users
4. *small focus group with a stakeholder group* was carried out with six water users
5. *large focus group* was carried out in a large group setting with thirty water users.

Table 3.3 Pilot study settings

	Individual interview	Small group interview	Large focus group
Water experts	Pilot study 1	Pilot study 2, 3	-
Water users	-	Pilot study 3, 4	Pilot study 5

These settings evolved as part of the process. The process first began with an interview with a water expert (pilot study 1) and a small focus group with two water users (pilot study 2), in order to obtain some preliminary feedback on the workbook from the experts. It was found that the dynamic was better in a group setting. As such, different group settings with a mixture of water users and water experts were trialled (pilot study 3 and 4). Due to practicality, a large focus group was carried with only the water users because it was easier to arrange (pilot study 5).

The following is a summary of the findings from these five pilot tests:

- Based on all pilot tests, the author observed that there was a high level of interaction between the study subjects and the researcher. Many questions were raised during the elicitation process by the study subjects in relation to the case study problem (for further information) and workbook (how to fill in the workbook). The questions raised during the pilot study were used to improve both the workbook and the narrative component of introducing the decision making problem. This also confirmed the validity of using the interview and focus group.
- Homogeneous stakeholder and focus groups were better than mixed stakeholder/focus groups because the process could then not be dominated by subjects with greater knowledge of the topic.
- Individual interviewing and small focus groups were the preferred methods compared to the large focus group mainly because the researcher could spend more time answering questions with a smaller group of participants. Also a large focus group required more time to address individual concerns.

Main study

After the pilot study, the next phase of the research was the main study. The purpose of the main study was to collect actual data for the research by administering the revised workbook in the selected settings (individual interview and small focus group). The main study was carried out in a homogeneous setting (no mixture between water users/manager/experts) over a series of interviews and small focus groups. The duration of an interview or focus group varied between 1 to 3 hours depending on the size of group and also the study subjects involved. In the entire main study, four water experts, two water managers and twenty water users were interviewed (n = 26).

Table 3.4 Pilot study and main study

Research activities	Number of study subjects
1st pilot test (individual interview)	1 water expert
2nd pilot test (small group interviews)	2 water experts
3rd pilot test (small focus group with mixed study subjects)	1 water experts + 3 water users
4th pilot test (small focus group with homogenous study subjects)	6 water users
5th pilot test (large focus group)	30 water users
Total number of pilot study subjects	43
Main study	4 water experts + 20 water users + 2 water managers
Total number of main study subjects	26

Rationale for sample size

It is necessary to re-iterate the research objectives here in order to provide justifications for the selection of a sample. As described in Chapter 1, the research objective was to develop a method to account for judgement uncertainty and criteria interaction for aiding urban water decision. A secondary objective which sprang from this main objective was to test-proof the method using a selected sample of study subjects. From this perspective, it was not the aim of this thesis to validate the approach. Hence, the group may be considered as a selective sample, but the nature of the research meant that it was sufficient for the purpose and was within time and cost limitations.

On the other hand, if there was no resource or time limit imposed on this research project, the research could have been carried out with the same group of study subjects over a longer period of time. This type of longitudinal study (to permit observations over a period of time) would provide greater insights into how judgement uncertainty and criteria interaction affect judgement over time. More time to evaluate individuals' preferences could have allowed for greater precision, nonetheless, a 'proof-of-concept' in the approach was the prime goal here.

The absolute reference population is one of the key factors in determining the sample size (Guadagnoli and Velicer, 1988). In total, 69 participants were recruited to participate in this study (43 in pilot study and 26 in main study). Although the sample size in the main study was relatively small from which to make statistically justified conclusions for the population, the percentage of the sample selected for the water users and water expert group was up to 20% of the reference population. The target population was required to have sufficient understanding of urban water systems and the associated issues, thereby limiting the size of the target population. In the School of Civil and Environmental Engineering in 2009 semester 2 and 2010 semester 1, there were about a hundred postgraduate/4th year undergraduate students enrolled in the environment engineering course at the time the research was conducted. A total of 39 postgraduate students acted as water users in the pilot test, and another 20 postgraduate students as water users in the main survey (i.e. 20% of this reference population). As for the water experts, there were about 20 academic staff in our school who were experts in water engineering. The author interviewed four water experts in the pilot test and four water experts in the main test (i.e. 20% of this reference population). The samples were selected to give some variety in the participants' background and institutional contexts. The extent of these variation, together with the emphasis on in-depth methodology, suggest that statistical generalisations are no appropriate, and thus a small and diverse sample is considered acceptable.

Another rationale for the sample size selection was the size of the original GCWF Advisory Committee. In the GCWF project a group of twenty members comprising of community leaders, technical experts, industry representatives, local government councillors and council representatives formed an advisory committee. They met on a monthly basis to investigate the alternatives over a period of twenty months. It was not the aim of this research to model the decision-making process of the advisory committee over the same period of time. Rather, this research mimicked the initial phase of the advisory committee for the GCWF project, in which opinions were diverse and understanding differed. Uncertainties in this situation were twofold. Firstly, there were uncertainties associated with the external environment, concerning the information obtained, extent of knowledge and doubt about any related decision. Secondly, there were uncertainties associated with the DMs' judgement, concerning the impreciseness of their preference. These two types of uncertainties are inter-related because the amount of information offered and the extent of the participants' knowledge influence the impreciseness of their judgement. In this situation, this study observed the impreciseness of individuals' judgement under the circumstances when they were first introduced to the problem. This fitted well with the aim of modelling individuals' judgement uncertainty because it was expected that the participants' judgement would be imprecise during the early phase of the decision making process. This study provided some insights to how DMs make judgement under these two forms of uncertainties.

Analysis

By this phase, the three types of data required were collected (Figure 3.4):

- performance data for all criteria
- perceived criteria importance from the study subjects
- observed global values from the study subjects.

The analysis components of the research contain the following:

- *Construction of the four preference models* (Chapter 4) – was done using the elicited criteria performance data and criteria importance from the main study
- *Aggregation of the four preference models* (Chapter 5) – the four preference models were aggregated to obtain the calculated global values using Matlab 7.10 R2010a and MS Excel
- *Correlation analysis* (Chapter 5) – the software SPSS (Statistical Package for the Social Sciences) (version PASW Statistics 18.0.3) was used to determine the Pearson's correlations (r) and Spearman's rank correlations (r_s) between the calculated and observed global values
- *Sensitivity analysis* (Chapter 5) – this was carried out to examine the stability of the preferred alternative under changes to the criteria weights and criteria scores using Matlab 7.10 R2010a.

3.4 Case study – Gold Coast Waterfuture

The Gold Coast is located in the south-eastern corner of the State of Queensland, Australia (Figure 3.6). The city ranks as the sixth most populated city in Australia with a population of 515,200 in 2009 (Australian Bureau of Statistics, 2010). The Gold Coast has traditionally relied heavily on surface water, with water from the Hinze and Little Nerang dams as the main water sources. However, the Gold Coast is a fast growing region and its population is projected to double by 2056 based from the 2006 population figure of 500,000. The expected 'business as usual' water demand in 2056 is 466 million litres per day (ML/d).

Figure 3.6 Gold Coast, Queensland, Australia

Apart from the challenge of increasing population pressure, another problem faced by GCW is climate change. In 2002–3 the Gold Coast experienced a period of significant low rainfall, causing a crisis in the supply of water for the city. The situation forced the city council to rethink their water delivery strategy which led to the development of

Gold Coast Waterfuture (GCWF) in 2005, a long-term water strategy plan. This experience was typical among many major city water supply services in Australia.

3.4.1 Decision problem

The decision problem was to assess the overall sustainability of alternative strategies for the Gold Coast's urban water system. There were a range of initiatives included in the strategies and they were grouped as follows.

Significant water sources

The following water sources formed the key components of the water balance, Hinze Dam, Logan pipelines, southern regional pipelines:

- The existing Hinze Dam is about 15 kilometres south-west of Nerang and it has the capacity to provide on average 191 ML/d.
- The existing Logan pipelines allow bulk transfer of water from Wivenhoe Dam via Logan City and amount up to 35 ML/d.
- The proposed southern regional pipeline involves a two-way 94 kilometre pipeline that can move water between the Gold Coast, Logan and Brisbane. Out of the 130 ML/d that could be transferred in between the cities, 55 ML/d was proposed to be transferred to the Gold Coast. The southern regional pipeline was completed in 2008 and it is now an important component of the South-east Queensland water grid.

Supplementary water sources

Water conservation and pressure management are two supplementary water initiatives that contributed 50 ML/d and 20 ML/d water to the overall supply capacity respectively.

Emerging water sources

The proposed strategies differed in the contributions from the emerging water sources that could become part of the long-term water strategy. These were *raising dam capacity*, *desalination*, *recycled water* and *rainwater tanks*. A summary of the service levels and assumptions adopted in the development of each water source is in Table 3.6.

Table 3.5 Additional water sources considered in the GCWF project (Gold Coast Water, 2005)

Water source	Details	Assumptions
Hinze Dam augmentation	The existing Hinze Dam Stage 2 provided a yield of 191 ML/d (FSL 82.2RL)[7]. Two scenarios for raising the height of the existing dam wall: Hinze Dam Stage 2++ (FSL 83.5 RL) could yield 201 ML/d. Hinze Dam Stage 3 (FSL 93.5RL) could yield 215 ML/d.	Additional environmental flows were allowed for in the proposed augmentations of the dam.
Desalination	A desalination plant, located at Tugun, could provide an average of 133 ML/d of water. The project included a desalination plant, marine intake and outlet tunnels and a 25 kilometre pipeline connecting the plant to the South East Queensland water grid.	Desalinated water was mixed in reservoirs with potable water from surface water supplies.
Rainwater tanks	Large scale implementation of rainwater tanks in both new development areas and some brownfield areas. The target was to provide 20 ML/d to the city by 2056, from the level of 0.5 ML/d in 2005.	If a recycled water service was provided, rainwater would be used for laundry, bathroom, and hot water systems. If a recycled water service was not provided rainwater would be used for toilet flushing, garden irrigation and external maintenance.
Recycled water	Reuse recycled water up to 50 ML/d, generated from four reclamation facilities.	Use Class A+ for toilet flushing, garden irrigation, ext'l maintenance, air con. cooling tower water.

The water balance is shown in Figure 3.7. The decision problem was to determine the level of contribution for each component of the emerging water sources. Five strategies were proposed in GCWF (2005) with different emphasis on the four emerging water sources.

[7] FSL – Full Supply Level; RL – Retention Level

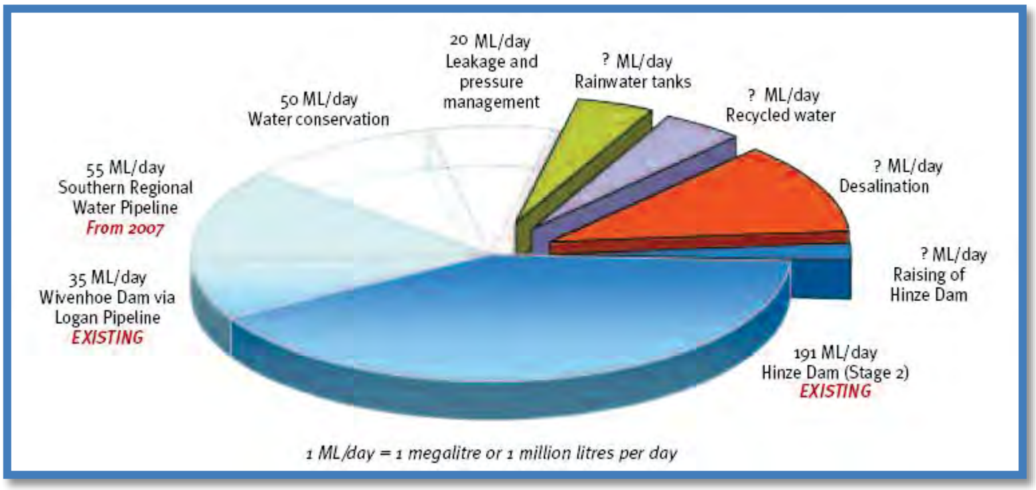


Figure 3.7 GCWF water balance (Gold Coast Water, 2006)

The strategies are described as follows:

- ***Strategy A: raise dam capacity*** – incorporated the raising of Hinze Dam, moderate supply contributions from rainwater tanks and recycled water and eventually a moderate seawater desalination supply. This was the most conventional strategy because it maintained a high reliance on Hinze Dam as the major water source.
- ***Strategy B: desalination*** – considered the implications of using seawater desalination as the main future source of water supply with minor contributions from recycled water and rainwater.
- ***Strategy C: balance*** **–** like Strategy A, assumed that Hinze Dam was raised, but to a lower extent. It also assumed a lower usage of recycled water and therefore a higher long-term reliance on seawater desalination.
- ***Strategy D: without raising Hinze Dam*** – was essentially the same as Strategy A except that it considered the implications of not raising Hinze Dam.
- ***Strategy E: recycled water and rainwater tanks*** – assumed that the use of rainwater and recycled water would be developed to a significant level, reducing the long-term reliance on seawater desalination.

Strategy B and D were the only strategies without raising dam capacity. To make up for the demand, strategy B had a strong emphasis on the desalination component and strategy D had more supply from rainwater and recycled water. Strategy A had the largest contribution from raising dam capacity, thereby making it the most conventional approach. Strategy C and E, on the other hand, had less contribution from raising dam capacity and a more balance contribution from the other three resources. Therefore, strategy C was known as the balance option and strategy E, with higher proportion of supply from rainwater tanks and recycle water, was known as the 'greener' option. The breakdown of components for each strategy is shown in Table 3.6. The contribution of each emerging water source without the significant and supplementary water sources are shown in Figure 3.8. The pros and cons for each strategy are listed in Table 3.7.

Table 3.6 Breakdown of water sources contribution for strategies A–E (Gold Coast Water, 2005)

Water Sources (ML/d)	A	B	C	D	E
Significant water sources					
Existing Hinze Dam	191	191	191	191	191
Logan pipelines	35	35	35	35	35
Southern regional pipelines	55	55	55	55	55
Supplementary water sources					
Water conservation	50	50	50	50	50
Pressure management	20	20	20	20	20
Emerging water sources					
Raise Hinze Dam	24	0	10	0	10
Rainwater tanks	20	5	20	20	32
Recycled water	40	15	15	40	50
Seawater Desalination	31	95	70	55	23
Total Supply Capacity	466	466	466	466	466

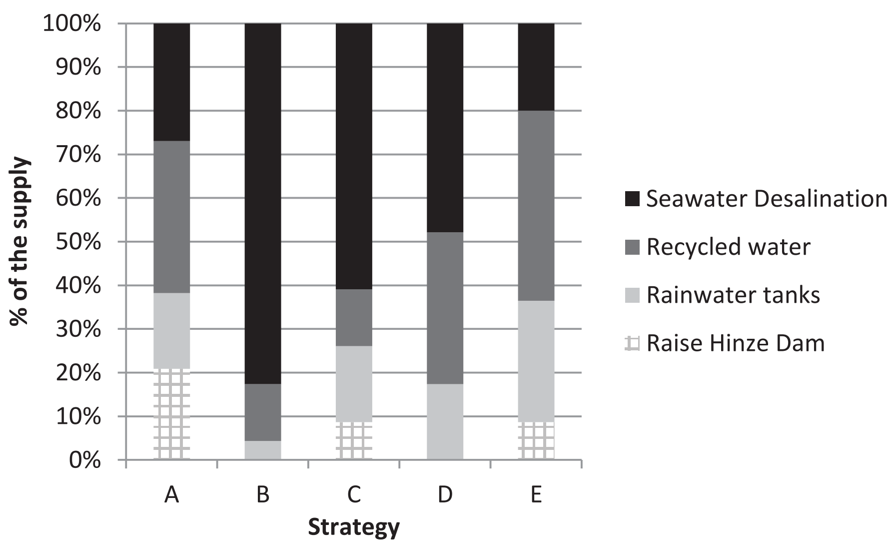


Figure 3.8 Comparison between the five strategies A to E (adopted from Gold Coast Water (2005))

Table 3.7 Pros and cons of the five water strategies

Strategy	Details	Pros	Cons
A Raise dam capacity	Most conventional strategy. Incorporates raising of Hinze Dam. Moderate supply contributions from rainwater, recycle water and desalination.	Business as usual. Less complex infrastructure (rainwater/recycle water).	Reliability issues with the dam. Flexibility low. Drought restriction. Ecosystem disturbed.
B High Desalination	Assumes that Hinze Dam is not raised. Desalination as the main future source. Rainwater and recycled water not major source.	Lower life cycle cost (lower operation cost from rainwater and recycled water). Less likely to warrant water restriction.	High greenhouse gas emission.
C Balance	Assumes that Hinze Dam is raised. Lower usage of rainwater tank and recycled water. Higher long term reliance on desalination.	Balanced range of initiatives. Higher likelihood of community acceptance. High flexibility.	Moderate to high greenhouse gas emission due to relatively high reliance on desalination.
D No dam raising	Essentially the same as Strategy A except Hinze Dam is not raised.	Better environmental performances.	Low likelihood of community acceptance.
E Recycled water and rainwater tanks	Assumes that Hinze Dam is raised. The use of rainwater tank and recycled water will be developed to a significant level. Reduce the long-term reliance on seawater desalination.	Better environmental performances. High exposure to risk due to complexity of infrastructure.	Highest life cycle cost. Lower likelihood of community acceptance. High impact on local community due to brownfield implementation.

3.4.2 Decision making process in the GCWF project

Water Services Association of Australia, the peak body of Australia urban water industry developed a sustainability framework in 2005 to support the water industry in its long-term planning. The framework is comprised of six phases as shown in Figure 3.9. Although, the GCWF was devised independently from the WSAA sustainability framework, the two shared a number of similarities (Lundie *et al.*, 2008a). The process flow diagram of the GCWF decision making process is depicted in Figure 3.10.

It is not part of this study's aim to compare the difference between the two processes (WSAA and GCWF), for further information refer to Lundie *et al.* (2008b). The WSAA framework is referenced here to illustrate which phase in the decision making process this study concentrated on. In the context of WSAA sustainability framework, Phase 5

Generation of performance matrix and Phase 6 Identify preferred option by applying MCDA approach were the two phases of interest.

This study adopted the initial problem structuring (Phase 1 to Phase 4) from the GCWF project with some modifications made to Phase 3 to eliminate double counting in the selected criteria (Section 3.4.4 p.103). The task undertook in this study was to re-generate a new set of performance matrices which could provide the required information to test-proof the new MCDA method developed as part of this research.

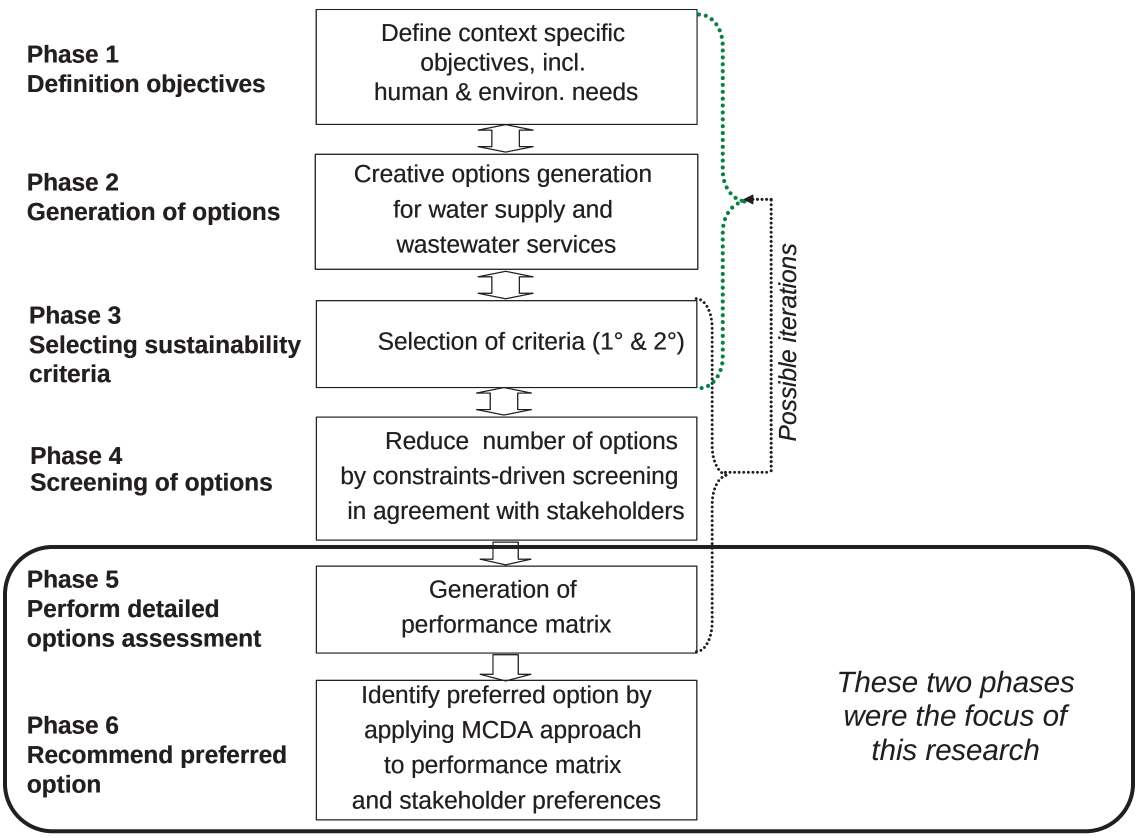


Figure 3.9 Research problem linked to WSAA sustainability framework (Lundie *et al.*, 2008a)

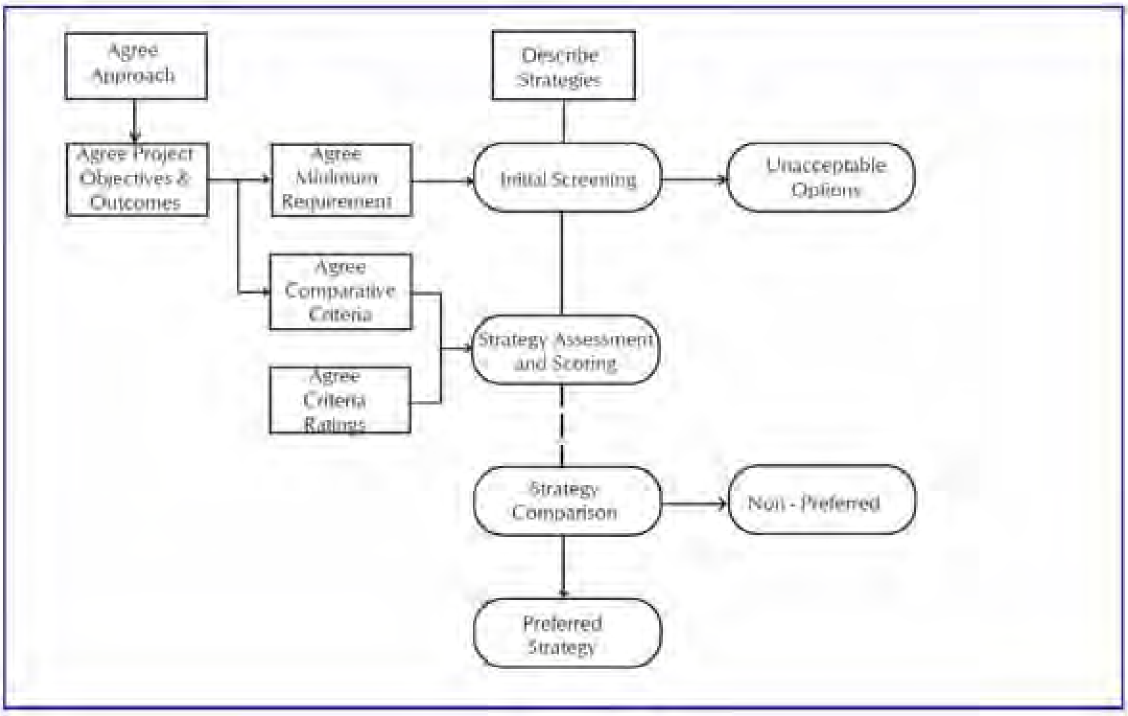


Figure 3.10 Decision making process flow diagram in GCWF project (Lundie *et al.*, 2008b)

The GCWF generally shared the same process with respect to the WSAA framework but there were some subtle differences detailed as follows (Lundie *et al.*, 2008b):

- *Established common knowledge base* – during the problem structuring phase of the GCWF project, terms of reference were established which dealt with the rules of collaboration and understanding of the water cycle management. This common knowledge was valuable in establishing common understanding within the Advisory Committee.
- *Alternative focused thinking* – screening of options was carried in an early phase of the GCWF project prior to the selection of criteria. This process focused on alternatives rather than values, which could potentially limit the space for innovative ideas or alternatives to be generated (Keeney, 1994). In contrast, the screen of options happens at a later stage in the WSAA framework (phase 4) and iterations are allowed for ideas to evolve. This is an example of a decision making process driven by value focused thinking which focuses on eliciting the DMs' values prior to identifying alternatives. However, it should be noted that consideration of

alternatives can also provide useful stimulus for thinking about values (Belton *et al.*, 1997).

- *Aggregation and criteria structure* – the main difference between the GCWF project and WSAA framework was in the aggregation phase and the structure of the criteria value tree. The difference is detailed in the following section.

3.4.3 Multi-criteria approach in the GCWF project

The value function adopted in the GCWF project was different from the conventional weighted sum approach. Instead of structuring the problem into the conventional triple bottom line (i.e. environmental, social and economic), the GCWF project categorised the problem into two components, cost and non-cost. For the cost component, the whole of life costs approach was taken to quantify the net present values of the different strategies. For the non-cost component, the scores for environmental and social criteria were normalised and aggregated into a single score. The non-cost score was divided by the cost score to obtain a final performance score (value for money) for each strategy. The relationship between non-cost score, cost score and value for money is illustrated below. The process is illustrated in Figure 3.11.

$$\text{Value for money} = \text{Non-cost score} \div \text{Cost score}$$

This process differed from the weighted sum approach in which the non-cost and cost components were aggregated differently. It was not clear the reason why this aggregation function was adopted in the assessment, but the approach was agreed by the Advisory Committee. The financial component shown in Figure 3.11 is different from the cost component. The financial component refers to extra financial information considered by the Advisory Committee to allow for a high level comparison of the strategies. This includes the expected one-off increase in water and wastewater infrastructure charges, total recurrent water charges and maximum gross debt for each strategy.

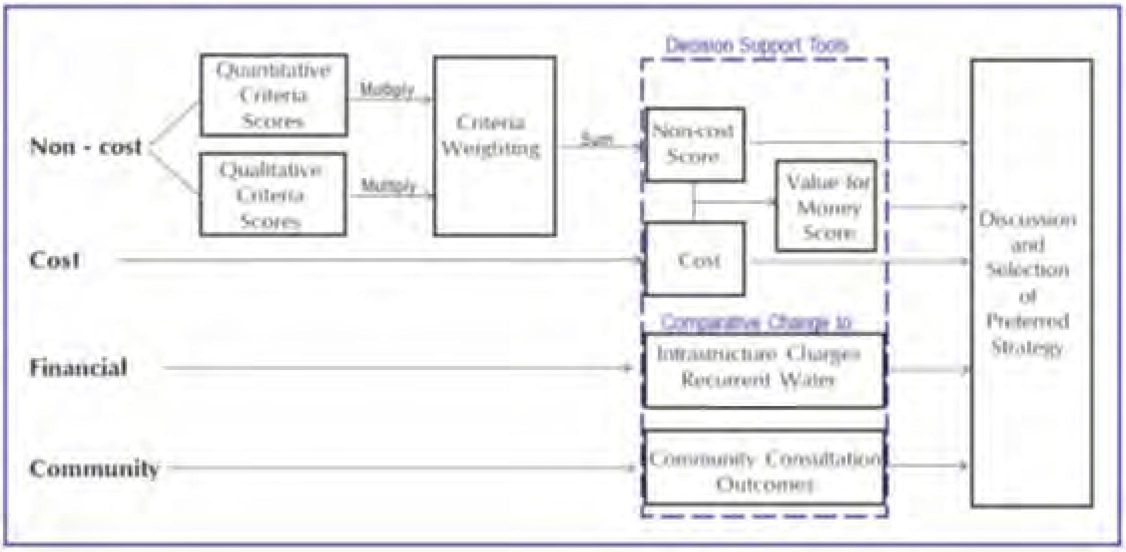


Figure 3.11 Decision making process in the GCWF project (Gold Coast Water, 2005)

3.4.4 Problem structuring

This section reviews the original structure of the criteria hierarchy in the GCWF assessment. There were 12 non-cost and 1 cost criteria considered in the GCWF project. The criteria were grouped by environmental, social and economic aspects as shown in Table 3.8. The criteria were measured either qualitatively (5 criteria) or quantitatively (8 criteria). Qualitative criteria were assessed by the Advisory Committee on a scale of 1 to 5 for each strategy, where 1 referred to the worst and 5 the best.

The author highlights the specific instances of double counting and criteria interaction found in this original criteria hierarchy. This section demonstrates the issues of double counting and criteria interaction qualitatively. Double counting can be eliminated by restructuring the criteria but for interacting criteria they are first identified and modelled. To achieve this, the criteria for this case study was modified and restructured to first eliminate double counting criteria and to highlight interacting criteria. Modification of the criteria hierarchy is made as presented in the next section (Section 3.4.5 p.109).

The purpose of stage 1 is to eliminate double counting by identifying relationships between the criteria through value focused thinking. The technique begins with identifying the fundamental criteria and connects the related means-ends criteria:

- *Fundamental criteria* – reflect the fundamentally objectives in the decision context. They are defined to be *essential* (reflect the fundamental reasons for interest in the decision problem) and *controllable* (address the consequences that are influenced only by the choice of alternatives in the decision problem). They should also possess the desirable properties listed in Section 2.5.2 p.46.
- *Means-ends criteria* – elaborate the means by which the fundamental values occur. They should represent the causes or consequences by which the impacts (fundamental value) occur.

The key difference between the two is the fundamental criteria indicate why there is an interest in a problem, and the mean-ends criteria suggest the network of factors that contribute to the interest in a problem.

With the mean-ends criteria, the relationship between adjacent levels is causal and therefore they are best depicted by a network. In contrast, the relationships between the fundamental criteria are distinct. The relationships are best captured in a hierarchy format because the lower level fundamental criteria (secondary criteria) should be mutually exclusive and collectively provide exhaustive characterisation of the higher level criteria (primary criteria).

Table 3.8 Original criteria in the GCWF project (Gold Coast Water, 2005)

	Outcome	Criteria	Proposed measures
Environmental			
1	Minimum impact of construction on ecosystems	QUALITATIVE Construction impacts	Short-term impacts of construction activities
2		QUANTITATIVE Land clearing required	Estimated area of vegetation to be disturbed
3		QUALITATIVE Loss of high value ecosystem	Relative area and significance of high value ecosystem significantly disturbed (including impacts due to land clearing and loss of / changes to aquatic habitat)
4	An environmentally sustainable strategy	QUALITATIVE Potential impact on environment	Impacts on: regional or local biodiversity; water health; wastewater or other waste discharges; surface or groundwater quality; environment due to reduced wastewater discharges; soils (due to reuse)
5		QUANTITATIVE Greenhouse gas emissions	Net per capita greenhouse gas emissions for water supply
Social			
6	A secure and reliable water supply	QUALITATIVE Minimum reliability of service	Likelihood that water restrictions will be required during drought
7		QUANTITATIVE Security of water supply index	Security of water supply index. The higher the score the greater the security
8		QUALITATIVE Adaptability to change	Ease with which strategy can be changed to accommodate different future water demands or other unforeseen requirements
9	Ensure fit for purpose water quality	QUANTITATIVE Water quality fit for purpose index	Extent to which water supplied has been treated to an appropriate standard for the particular purpose
10	Broad community acceptance of strategy	QUALITATIVE Impacts on local community	Extent to which the strategy results in localized community disruption or dislocation
11		QUALITATIVE Community acceptance	Likelihood that the community will accept the proposed strategy. Assessment to be based on input from Advisory Committee and Consultation Program. Acceptance includes issues of overall amenity of the strategy and equity.
Economic			
12	An acceptable risk profile	QUALITATIVE Significant long or short-term risks	Extent of significant engineering, environmental, community or legal risks arising from risk management exercise
13	Minimise whole of life costs	QUANTITATIVE Whole of life costs	Whole of life costs to community for water supply services

The procedure to eliminate double counting is as follows:

1. Generate a list of criteria.
2. Identify the fundamental criteria by asking the question, '*Why is this criterion important*?'. A fundamental criterion is important because it simply represents a valued principle. A means-ends criterion is important because it has implications on the fundamental criteria.
3. List the fundamental criteria and connect them to the related means-ends criteria. The author proposes to use the concept of '*from and to*' and identify the flow of relationship between the two types of criteria as opposed to the traditional criteria tree that is grounded on '*is*' and identity. Fundamental criteria represent the values of the DMs (from) which the means-ends criteria are connected to because they represent the means that by which the fundamental values are influenced (to).
4. Some fundamental criteria can also pose as means-end criteria. In this situation, the criteria interact and a different decision model should be employed such as Choquet integral to derive the global values for this group of criteria.
5. Construct a criteria structure with means-ends criteria as sub-criteria to the related fundamental criteria.

Out of the 13 criteria reported in the GCWF, 10 were identified as fundamental criteria, 2 as means-ends criteria. The fundamental criteria are listed on the first column of Table 3.9 and the related means-ends criteria are listed in the second column. There were two instances of double counting identified from Table 3.9. The relationships between the criteria are illustrated in Figure 3.12

Table 3.9 Fundamental and means-ends criteria

Fundamental criteria (From)		Means-ends criteria (To)
1	Short-term construction impact	
3	Loss of high value ecosystem	2 Land clearing; 4 Potential impact on environment
5	Greenhouse gas emissions	
6	Reliability	
7	Security of supply	
8	Adaptability to change	
10	Long-term impact on social community	
11	Community acceptance	
12	Risks	
13	Whole of life costs	9 Water quality fit for purpose

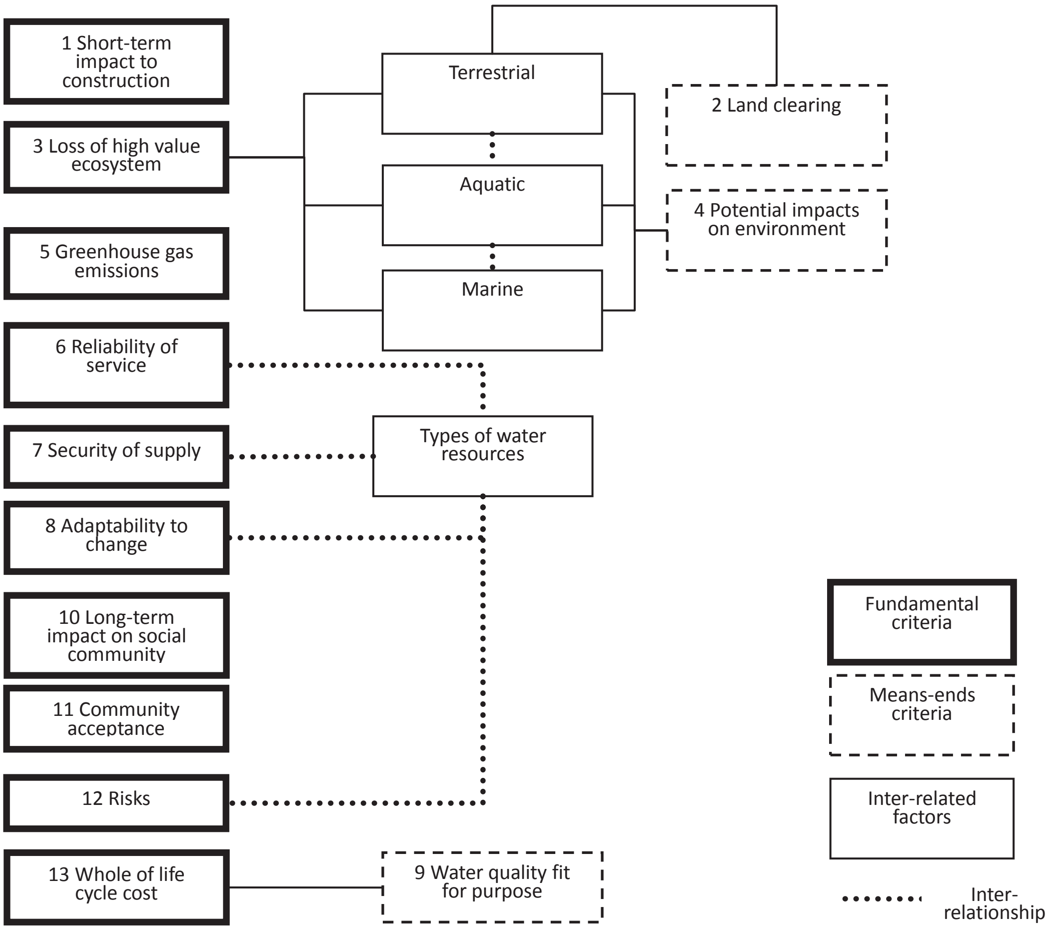


Figure 3.12 Identify fundamental and means-ends criteria, interaction in the original value tree

Double counted criteria

There were two instances of double counting in the GCWF criteria. The first stance of double counting was between the following criteria:

- *Criteria 2. Land clearing* – gross area of land disturbed in hectares to implement a strategy
- *Criteria 3. Loss of high value system* – relative area and significance of high value ecosystem significantly disturbed
- *Criteria 4. Potential impacts on environment* – measured long-term impacts on biodiversity, waterway health, wastewater discharge.

In the original value tree in the GWCF project (Figure 3.13b), there were two primary criteria and five secondary criteria under the environmental category. According to value focused thinking, in the environmental category, only the criteria ‘loss of high value ecosystem’ and ‘greenhouse gas’ (representing climate change) were fundamental criteria. The other two criteria were means-ends criteria, representing the *cause* (criterion 2 land clearing) or *consequence* of the fundamental criterion (criterion 4 potential impacts on environment). In the original value tree, ‘land clearing’ was considered as a secondary criterion. The influence of land clearing was also double counted in criterion 4 ‘potential impacts on environment’. This was the case because land clearing had potential impacts on the environment, by disturbing significant terrestrial habitat and thus significant fauna and flora species.

In the value focused thinking diagram (Figure 3.13a), the three environments of the ecosystem (terrestrial, aquatic, marine) were considered as fundamental but secondary criteria to the primary criterion ‘loss of high value ecosystem’. Criteria weights were placed on the fundamental criteria only. The interaction between ‘land clearing’ and ‘potential impact on environment’ were taken care of in the means-ends criteria hierarchy, thereby eliminating redundancy.

The second instance of double counted criteria in the GCWF project was between:

- *Criteria 9 Fit for purpose* – a measure of the extent to which water was not over-treated (e.g. not treated to a higher standard than required for a particular purpose).
- Criteria 13 Whole of life costs.

Criteria 9 ‘fit for purpose’ was an index calculated by dividing the amount of non-drinking water supplied by the total potential amount of non-drinking water. A higher score indicated that less water was being over-treated. This index could be directly translated into costs of treatment which was already factored in the ‘whole of life costs’ criterion (Figure 3.14b). ‘Fit for purpose’ was a means-ends criterion to reflect on the efficiency of the water supply system. It was not a fundamental criterion because it had implication on a more fundamental value, which was the efficiency of treatment. The criterion ‘fit for purpose’ was double counted for in ‘whole of life costs’.

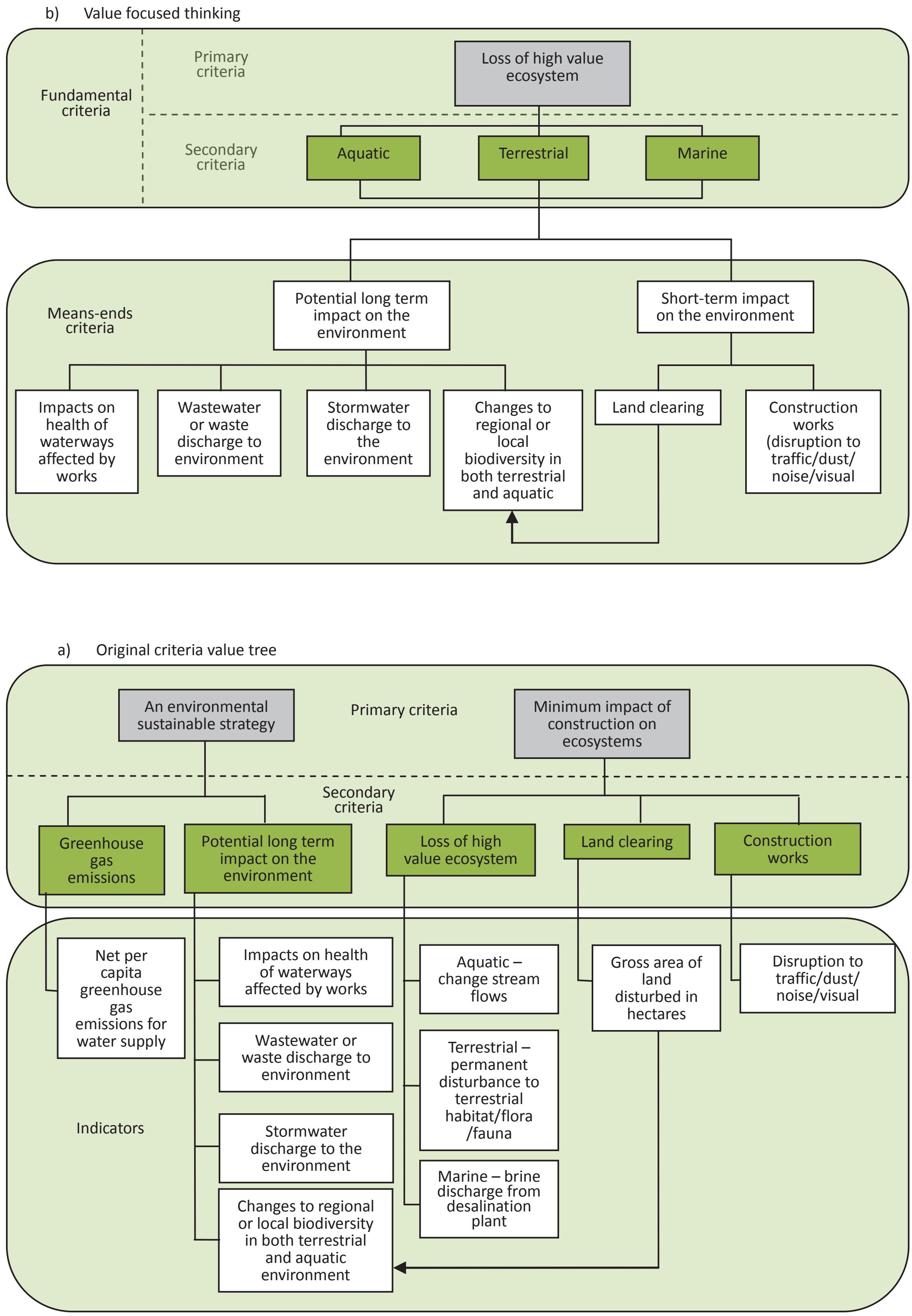


Figure 3.13 Illustration of double counting in the environmental category (a) value focused thinking (b) original criteria value tree

Using value focused thinking, 'whole of life cycle cost' was nominated as the fundamental criterion (Figure 3.14a). In fact, a more suitable fundamental criterion in replacement of 'whole of life cycle cost' would be value for money. 'Whole of life cycle cost' only reflected the costing side of economic evaluation but did not capture the value for money. This differentiation was not illustrated in Figure 3.14a because there was no data to measure this criterion in the subsequent analysis.

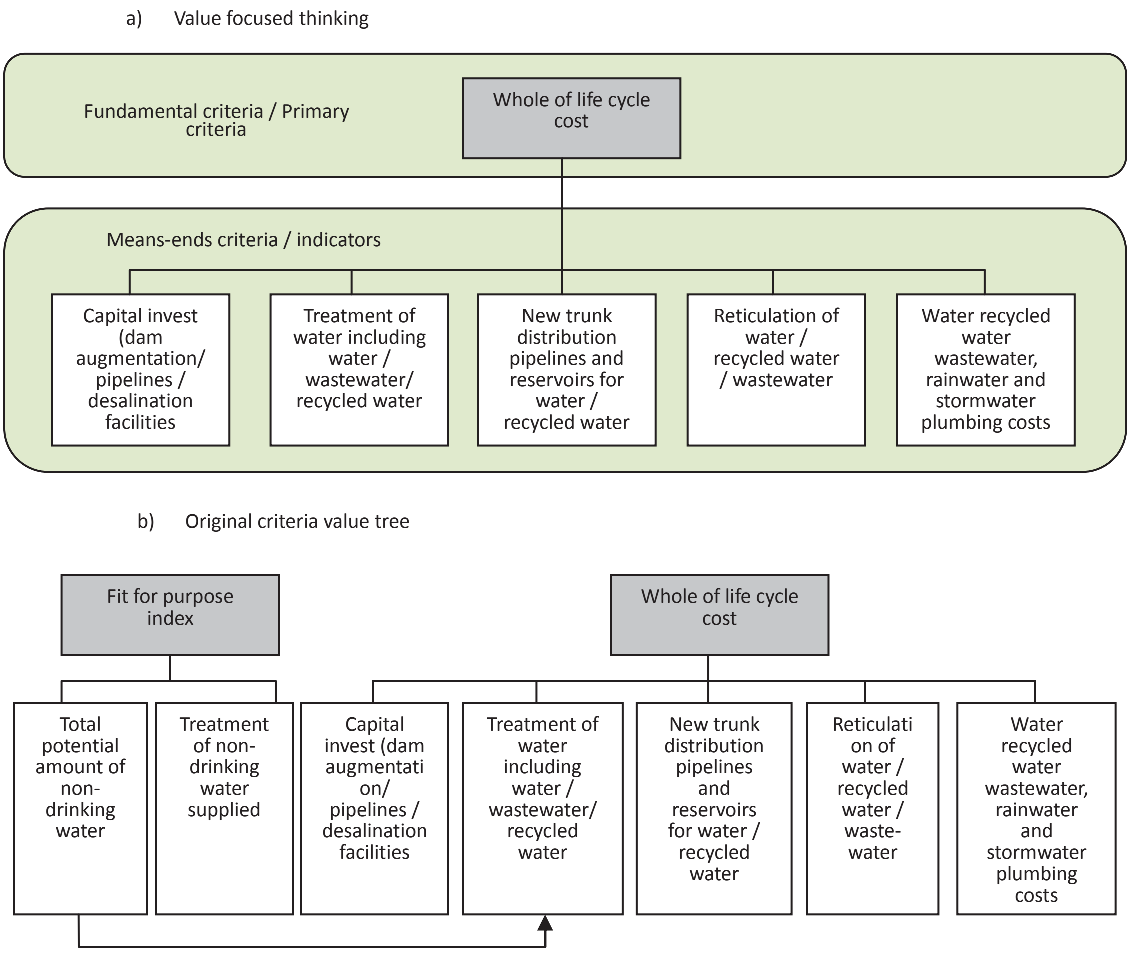


Figure 3.14 Illustration of double counting in the economic category (a) value focused thinking (b) original criteria value tree

Criteria interaction

There were two instances of criteria interaction in the GCWF project identified from Figure 3.12 (interacting criteria are linked by dotted line). The first instance of criteria interaction was between:

- *Criteria 2. Land clearing* – gross area of land disturbed in hectares to implement a strategy
- *Criteria 3. Loss of high value system* – relative area and significance of high value ecosystem significantly disturbed.

The impact of dam raising included forest clearing, affecting significant flora and fauna species and further impeding the health of downstream waterways. The preferential independency condition was violated in this situation because there were interactions between these impacts. Floral and faunal habitats were directly affected by forest clearing. If these three criteria were considered as mutually independent, the impact on the environment would be over-emphasised. The clearing of forest included not only remnant vegetation but as also riparian vegetation which could affect the macro-invertebrates community in the downstream waterways.

The second instance of criteria interaction in the GCWF project was between:

- *Criteria 6 Reliability of service* – considers the ability of the strategies to reliably meet the community's water demand
- Criteria 7 *Security of supply* – measures the number of significant water sources included in each strategy
- *Criteria 8 Adaptability to change (flexibility)* – considers how easy it will be in the future to adapt each strategy to take account of changing demographics, demand pattern, technologies etc
- *Criteria 12 Risks* – addresses the significant long or short-term risks that potentially affect the successful implementation or operation of the water supply strategies.

Similar to the ecosystem criteria, interactions occurred between the technical criteria ('security of supply', 'reliability', 'flexibility' and 'risks'). 'Security of supply' measured the diversity of water supplies. 'Flexibility' referred to the availability of different operational modes in response to changing environments. The greater the number of alternative water supplies, the more flexible the system is but asset stranding is greater. ‘Risks’ referred to the overall system risks, measuring the likelihood of system failure. ‘Reliability’ measured the degree of dependency on climate sensitive water resources. The greater the dependency on climate sensitive water resources, the lower it is for reliability. All of the criteria relate in one way or the other to the different water supply resources.

3.4.5 Modification to the criteria

Information on the following criteria was largely based on the 2005 GCWF assessment report (Gold Coast Water, 2005). The new criteria value tree (Figure 3.15) was restructured from the original value tree (Figure 3.16). Instead of having only three categories, the new value tree was expanded into the following four categories and a subcategory:

- *Social* – long / short-term impacts on the community and likelihood of community’s acceptance
- *Environment* – loss of high value ecosystem and greenhouse emission:
- Ecosystem – impacts on terrestrial / aquatic / marine environment
- *Technical* – security of supply / reliability / flexibility/ risks
- *Economic* – whole of life cycle cost.

The criteria were regrouped for the following two reasons:

- *Group interacting criterion* – interacting criteria were grouped together for ease of comparisons. In the second stage of the decision support approach (Chapter 4), interacting criteria were evaluated as a group to obtain the importance of the interaction and the individual contribution of each interaction criterion to the coalition. Two groups of interaction criteria were identified in Section 3.4.4 p.108. They were grouped under ecosystem and technical criteria.
- *Eliminate double counted criteria* – only the fundamentally important criteria were considered in the restructured list of criteria.

Apart from the modification being made to the structure of criteria and categories, the following two individual criteria were also modified:

- *Fit for purpose index* – since this criterion was double counted with ‘whole of life costs’, this criterion could be eliminated from the assessment.
- *Risks* – information about the risks associated with the overall system operation was separately assessed. The risk assessment identified any significant risks that could have the potential to affect the successful implementation or operator of the water supply strategies. The assessment was not published and the author did not have access to it, therefore, the ‘risks’ criterion was taken as the health risks associated with cross contamination due to complex infrastructure of the recycle water systems.

The relationships between the modified and original criteria value tree are summarised in Table 3.10.

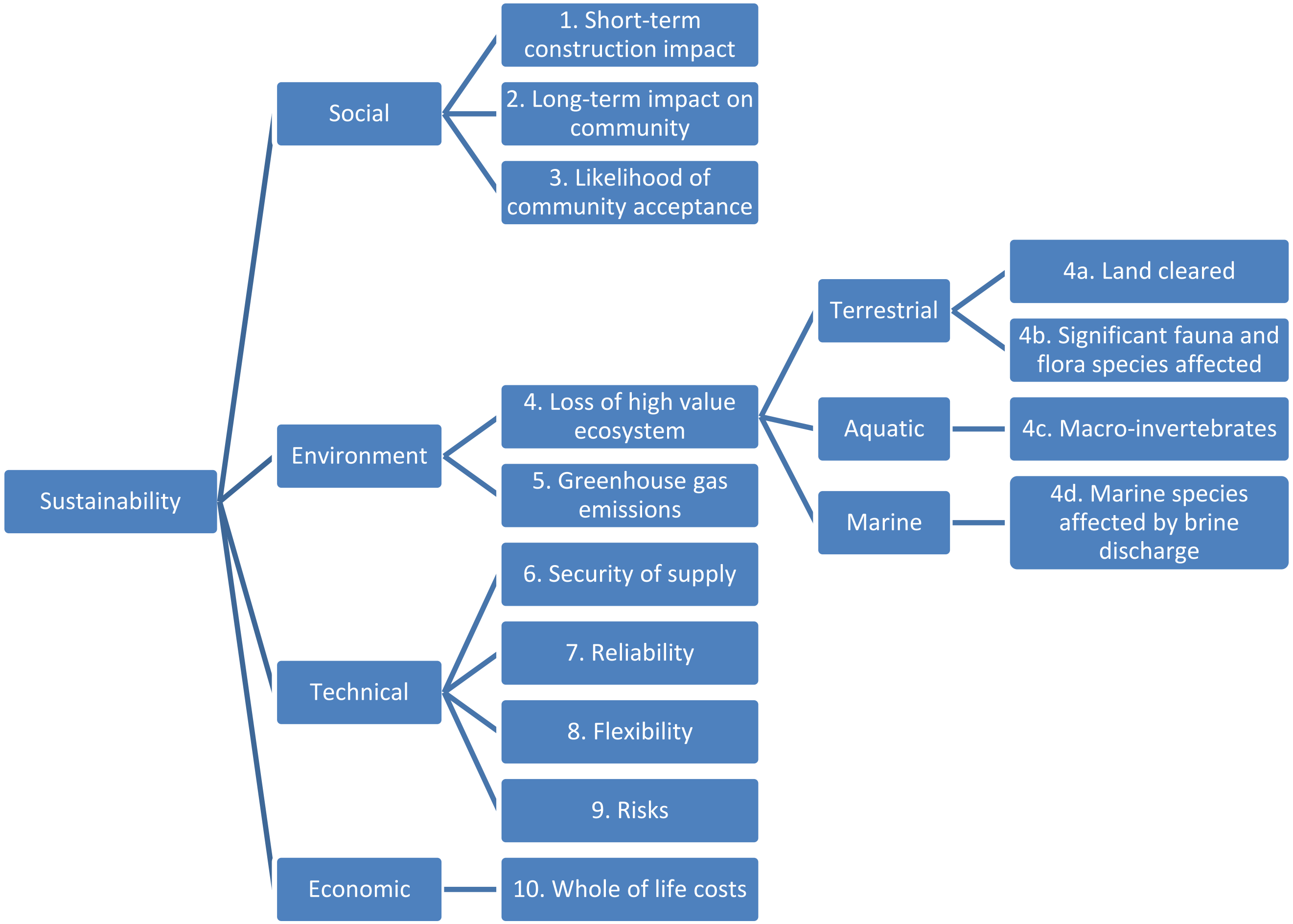


Figure 3.15 Restructured categories of the GCWF criteria for the study

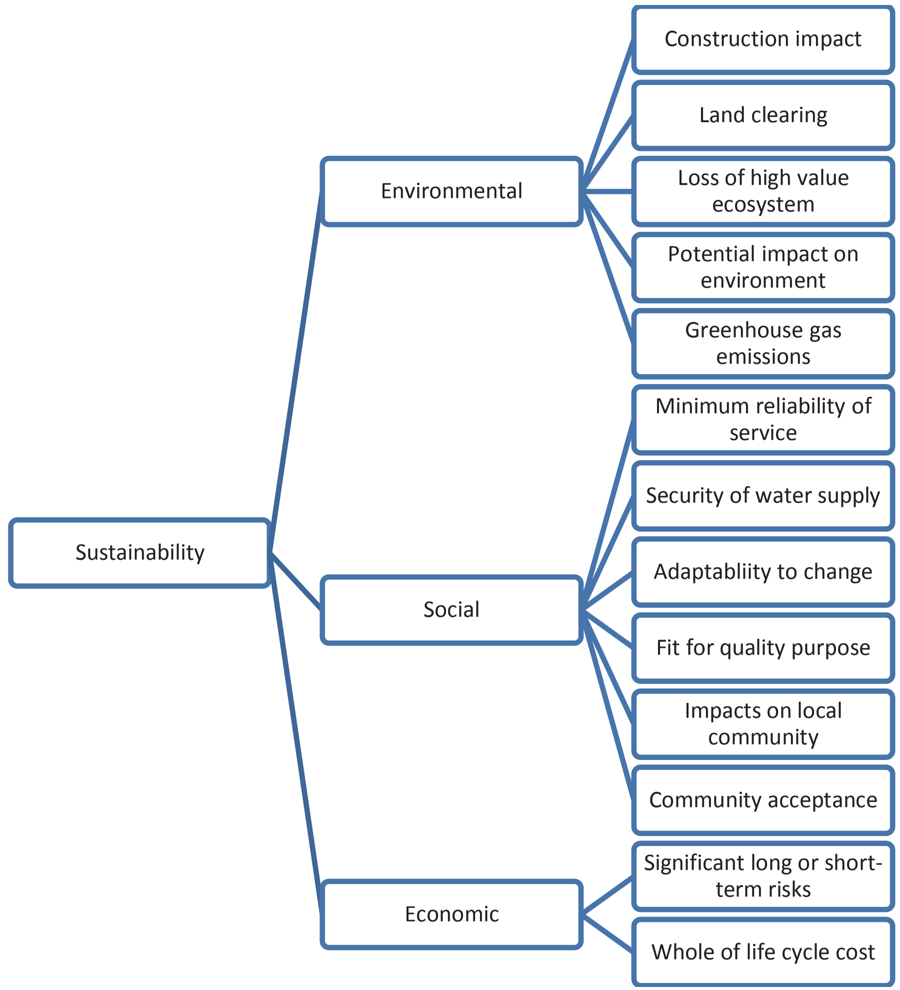


Figure 3.16 Original criteria value tree from the GCWF project (adapted from Gold Coast Water, 2005)

Table 3.10 Revised criteria and their relationships with the original criteria in GCWF project

Primary criteria	Secondary criteria	Original criteria	Double counted
Social			
1. Short-term construction impact	Air and noise quality; visual impact; relocation	(Environment) Construction impact	
2. Long-term impacts on local community	Extent of localised disruption to the community (i.e. pipelines construction in brownfield and relocation)	(Social) Impacts on local community	
3. Likelihood of community acceptance	Likelihood community will accept the proposed strategy	(Social) Community acceptance	-
Ecosystem			
4a. Forest	Estimated hectares of vegetation to be disturbed	(Environment) Land clearing	(Social) Loss of high value ecosystem (relative area and significance of high value ecosystem significantly disturbed)
4b. Flora & fauna	Flora species and fauna species	(Environment) Potential impact on environment (measure impacts on biodiversity, waterway health, wastewater discharge)	
4c. Macro-invertebrates	Macro-invertebrates as an indication of aquatic waterways health		
4d. Marine	Marine species affected by brine discharge		
Environment			
4e. Loss of high value ecosystem	Combine impacts from forest disturbance, loss of flora and fauna, macro-invertebrates and marine species	(Environment) Potential impact on environment	-
5. Greenhouse gas emissions	Net per capita greenhouse gas emissions for water and wastewater services	(Environment) Greenhouse gas emissions	-
Technical			
6. Security of water supply	The diversity of water supply resources	(Social) Security of supply	-
7. Minimum reliability of service	Likelihood that water restrictions will be required	(Social) Min. reliability of services	-
8. Flexibility	Ease with which strategy can be changed to accommodate different future water demands or other unforeseen requirements	(Social) Adaptability to change	-
9. Risk	Risks of system failure	(Economic) Risk	-
Economic			
10. Minimise cost	Whole-of-life costs to community for water supply services	(Economic) Whole-of-life costs	(Social) Fit for purpose is a measure of the extent to which water is not over-treated (over-treatment is translatable to costs)

Social criteria

c1 Short-term construction impacts

This criterion focused on the temporary impacts received by the sensitive residents during the construction phase, which were not expected to have long-term implications. The impacts included:

- temporary clearing to provide access
- waterways impacts due to excavation or sediment runoff
- disruption to traffic due to construction activities
- dust and noise generated by construction activities
- visual impacts of construction sites.

Measurement: Qualitative.

c2 Long-term impacts on community

This criterion was concerned with the long-term community effects arising from the strategies, including:

- dislocation or disruption to the communities due to construction works such as the inundation of the area surrounding Hinze Dam, the building of recycle water pipelines and desalination pipelines
- possible community benefits due to new infrastructure were also considered, such as the recreational uses for a dam, use of recycled water for garden and landscape irrigation
- initial and on-going costs borne to the community, which could include higher water tariffs and costs for installation and maintenance of rainwater tanks.

Measurement: Qualitative.

c3 Likelihood of community acceptance

This criterion incorporated community attitudes into the evaluation process, which aimed to reflect community perceptions about how the proposed strategies might affect them. Considerations were given to the following community attitudes toward:

- Hinze Dam: the perceived benefits of raising Hinze dam and the notion of Gold Coast being ‘independent’
- Rank water tanks: including amenity issues and costs

- Recycle water: acceptance of recycled water for different types of applications
- Sustainability issues: of energy use for pumping and desalination.

Measurement: Qualitative.

Ecosystem

c4a Land clearing required

This criterion measured the gross area of land disturbed in hectares to implement a strategy. Most strategies had a relatively small amount of land required except for Strategy A which required 440 hectares of native bush land for the highest level of Hinze Dam raising which could provide up to 24 ML/d. A lower level of Hinze Dam raising which could provide up to 10 ML/d required 50 hectares (Table 3.6). These figures did not account for compensatory planting as the cost of compensatory planting was factored into the whole of life cost.

Measurement: Quantitative (hectares of land).

c4b Significant fauna and flora species affected

This criterion was concerned with the permanent disturbance or loss to significant terrestrial habit which could affect significant fauna and flora species. The criterion was measured quantitatively by the number of significant fauna and flora species affected based on the Environmental Impact Statements of the strategies (Gold Coast City Council, 2006).

Measurement: Quantitative (number of significant fauna and flora species).

c4c Macro-invertebrates

The loss of macro-invertebrate community is frequently used as an indicator to reflect the health of waterways. Macro-invertebrates are animals without backbones, large enough to be seen with the naked eye, (e.g. snails, mussels, shrimps, crayfish, dragonflies, mayflies and midges). They are integral components of the aquatic food chain which are an important food source for fish and other vertebrates. The assessment of macro-invertebrates was based on the scheme from the Australian River Assessment System (Barmuta *et al.*, 2002)(Table 3.11). This assessment predicts the macro-invertebrate community that should present under reference condition or when a stream is healthy.

Table 3.11 Bands or categories of macro-invertebrate diversity for reporting (Barmuta *et al.*, 2002)

Band	Description	O/E Taxa	O/E Taxa interpretation
X	Greater biological diversity than reference sites	O/E greater than 90th percentile of reference sites used to create the model	More families found than expected. Potential biodiversity "hot-spot" or mild organic enrichment. Continuous irrigation flow in a normally intermittent stream.
A	Biodiversity similar to reference	O/E within range of central 80% of reference sites used to create the model	Expected number of families within the range found at 80% of the reference sites.
B	Biodiversity significantly reduced	O/E below 10th percentile of reference sites used to create the model. Same width as band A.	Fewer families than expected. Potential impact either on water and/or habitat quality resulting in a loss of families. Between 20% and 50% of the expected macro-invertebrate families have been lost.
C	Biodiversity severely impaired	O/E below band B. Same width as band A.	Many fewer families than expected. Between 50% and 80% of the expected macro-invertebrate families have been lost.
D	Biodiversity extremely impaired	O/E below band C down to zero.	Few of the expected families and only the hardy, pollution tolerant families remain. Severe impairment. Between 80% and 100% of the expected macro-invertebrate families have been lost.

Note: O/E Taxa is an index that compares the number of macro-invertebrate families expected to occur according to the predictions of the model and the number of those actually observed.

Measurement: Qualitative.

c4d Marine organisms affected by salinity

This criterion focused on the potential long-term impacts on the marine environment arising from brine discharge from the desalination plant. Although the impacts on the receiving water from brine discharge was expected to be relatively minor, primarily due to the dilution that would occur through the mixing effects of the outlet diffusers, consideration was given to the benthic communities. The establishment of stratification above the substrate due to salinity differences between the brine plume and overlying water, could lead to oxygen depletion, organism intolerance to increased salinity concentrations, release of metals and nutrients and changes to benthic community structure. The criterion was measured by the number of marine organisms with salinity tolerance level at or below the salinity level at mixing zone.

Measurement: Quantitative (number of marine organisms affected).

Environmental criteria

c4 Loss of high value ecosystem

The four criteria under ecosystem were considered secondary criteria under the primary criteria loss of high value ecosystem (Figure 3.15). This criterion was multi-dimension as it focused on the impacts on terrestrial, aquatic and marine environments.
Measurement: Quantitative (aggregate of four ecosystem criteria).

c5 Greenhouse gas emissions

The greenhouse gas emissions were expressed on the basis of per capita emissions (i.e. kilogram of CO_2-eq per person per year) and the figures for each of the strategies accounted for the following components:

- energy requirement for a range of systems and operational activities including water pumping, water treatment, recycled water treatment and desalination
- embodied energy (i.e. energy for manufacturing, transport and building the facilities).

Measurement: Quantitative (CO_2-eq per person per year).

Technical criteria

c6 Security of supply

The security of supply index measured the number of significant water sources included in each of the strategies and the variance of the capacity of these sources from the average capacity. A strategy with a high level of security of supply suggested that it had a high degree of diversity and secure sources. The index was calculated using the following formula (Gold Coast Water, 2005):

$$S_x = a - \left|\frac{\sum(b-c)}{c}\right|$$

Where,

S_x = security of supply index for strategy x

a = number of sources with yield greater than 10 ML/d

b = individual source capacity

c = average source capacity

The index was calculated on a yearly basis over the lifespan of the strategy (2005–2056) and hence it would vary from year to year. The overall security of supply index was taken as the average over that period of time.

Measurement: Quantitative (Security of supply index).

c7 Reliability

This criterion assessed the ability of the strategies to meet the demand at all times without the frequent need for water restriction. Consideration was given to each strategy's sensitivity to climate change. In particular, water sources such as Hinze Dam and rainwater tanks were considered as more sensitive to low rainfall and hence the possibility of water restriction would be required more frequently. Water sources such as recycled water and desalination were considered to be less sensitive to climate variability.

Measurement: Qualitative.

c8 Flexibility

Flexibility measured the ability of a strategy to be modified at any point during the life of the strategy to meet changing circumstances. For instance, if major works were committed too early in the beginning of the strategy life cycle, it would be much harder to implement the changes as there would be less opportunity to adjust the strategy in the future. Although it was anticipated that there would be no significant changes within the next 15–20 years since the proposed strategies should provide adequate capacity for that period of time. The works committed in the first period would affect the flexibility of the adopted strategy most significantly.

There were three significant changes that were anticipated to have implications on the strategy in the future:

- climate change which could affect the variability of rainfall
- technological advances could create new opportunities, or make existing technologies more cost-effective
- changing community attitudes could make it possible to exploit alternative water sources such as indirect potable reuse of recycled water.

Measurement: Qualitative.

c9 Risks

As explained earlier in Section 3.4.5 p.109, the risk criterion was taken as the health risks associated with cross contamination to reflect the complex infrastructure of the recycle water systems. This was because information about the risks associated with the overall system operation was separately not available. The health risk associated with cross contamination was measured in proportional to the amount of recycle water used in each strategy.

Measurement: Quantitative.

Economic criteria

c10 Whole of life costs

Whole of life costs or life cycle costs were calculated as the net present value of costs borne to the community for the water supply services considered in the strategies. The whole of life costs included the following costs:

- capital costs for the water sources such as dam augmentations, recycled water treatment plants and desalination plants
- the costs for treatment of the water including water, wastewater and recycled water treatment
- new trunk distribution pipelines and reservoirs for water, recycled water and wastewater
- reticulation of water, recycled water and wastewater
- water, recycled wastewater, rainwater and stormwater plumbing costs.

Measurement: Quantitative.

3.5 Conclusions

To address the identified four shortcomings from Chapter 2, this chapter outlines the proposed decision support approach. In particular, the design of the research program addressing the point of focus (what), selection of a sample (who) and research method (how) are presented. The following briefly summarises the findings:

- *Point of focus (what)* – a retrospective method using an existing and completed urban water decision problem, the GCWF as a case study was identified as the preferred method. The purpose of the study was to find out how well the decision support approach modelled the observed decision outcome.

- *Selection of a sample (who)* – the samples were selected from populations that the author had access to. Three groups of samples were selected from postgraduate students, academic staff and industrial personnel to represent water users, water experts and water managers.
- *Research method (how)* – through a series of pilot studies, individual interviews and small focus groups were identified as the preferred methods of collecting data from the samples. The findings from the pilot studies helped with the final main study. In total 69 participants were recruited in the study.

To test-proof the decision support approach, the first stage of the decision support approach, problem structuring, was applied to the GCWF case study in this chapter. The problem structuring phase involved restructuring the criteria according to value focused thinking, which was the selected tool to address double counting as discussed in Chapter 2. Through restructuring the criteria according to value focused thinking, two instances of double counting and two instances of criteria interaction were identified. In the restructured criteria value tree, double-counted criteria were eliminated and the criteria that interact were grouped together. The original thirteen criteria were reduced to ten criteria. The benefit in applying value focused thinking is that more meaningful trade-offs can be made by DMs when only the fundamental valued criteria are included in the value tree. If means-ends criteria (criteria that represent the causes or consequences of the impact stated by the fundamental criteria) were involved in the value tree, double counting could occur and the subsequent trade-off evaluation would not be meaningful.

4 Preference Elicitation and Modelling

4.1 Introduction

This chapter introduces the second stage of the decision support approach — preference elicitation and modelling. The framework has three stages as outlined in Section 3.2 p.71. The purpose of the preference elicitation and modelling stage is to obtain from the decision makers different sets of: (A) criteria weights and (B) criteria scores. Once the sets of criteria weights and criteria scores are obtained, they become inputs for the third stage of the decision support approach (aggregation) which is presented in Chapter 5.

The author introduces an innovative technique to elicit criteria weights and criteria scores to address the shortcoming, range sensitivity. In Section 4.2, the concept of mitigation and the associated elicitation technique are introduced. This technique was applied to the GCWF case study which was divided into four different cases. These four cases are described in Section 4.3, and were investigated to address two of the four identified shortcomings with MCDA use: (1) judgement uncertainty and (2) criteria interaction (see Chapter 2). The four cases represent different combinations of the shortcomings, with the first case being the conventional simple additive weighting approach not addressing any of the shortcomings; the second and third cases address the two shortcomings respectively; and the fourth case addresses both problems simultaneously. In all of the four cases, the procedures to elicit DMs' preferences are first described, followed by the presentation of examples from the case study to illustrate the procedure.

The highlights presented in this chapter are outlined as follows:

- *Mitigation value trade-offs* – a novel technique to elicit criteria weights and to normalise criteria weights
- *Mitigated normalising function* – a novel technique to normalise criteria score
- *Applied fuzzy simple additive weighting (FSAW)* – an algorithm to aggregate multi-criteria decision problems that takes into account judgement uncertainty
- *Applied Choquet integral (CI)* – an algorithm to aggregate multi-criteria decision problems that takes into account criteria interaction.

The following figure illustrates the structure of this chapter (Figure 4.1).

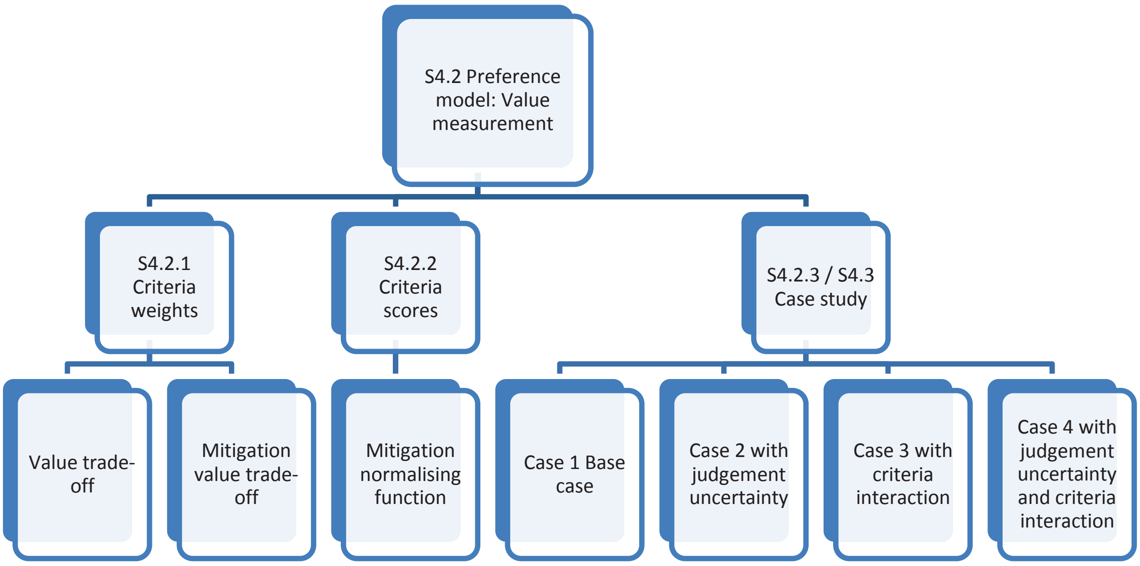


Figure 4.1 Structure of Chapter 4 – Preference elicitation and modelling

4.2 Preference elicitation

At this stage it can be assumed the problem structuring stage outlined in the previous chapter has generated a set of alternatives, and a set of fundamental criteria against which these alternatives are to be evaluated and compared. In order to assist DMs in their search for satisfactory decision outcomes, the task is to construct a model to represent their judgements. The purpose of modelling is to construct a view or perception of DMs' preferences consistent with a certain set of assumptions, in order produce a preference order on a set of alternatives. It should be noted that this preference modelling is one of the two tasks outlined in the DSM (Decision Support Methodologies) as discussed in Section 2.4.1 p.33.

The purpose of this section is to present two new techniques: one for eliciting criteria weights and another to normalise criteria scores. In order to understand the new techniques presented, it is important that the reader understand the basic concepts of a MCDA problem, which are presented as follows:

- *Alternatives* (A) – a finite number of alternatives to be considered as possible actions or candidates for the decision. An alternative can be referred to as an option or a strategy, like what it is described in the GCWF case study. A set of alternatives is defined as:

  $$A = (A_1, A_2, \dots, A_m \mid j = 1, 2, \dots, m)$$

  where j is the index for each alternative.
- *Criteria* (c) – each MCDA problem has multiple criteria. A criterion represents a particular value or interest according to which decision alternatives may be compared. The number of criteria can be between a minimum of two to hundreds. In urban water decision problems, the number of the criteria considered is usually within ten to fifteen. Criteria can be referred to as attributes which can be used interchangeably. A set of criteria is defined as:

  $$c = (c_1, c_2, \dots, c_n \mid i = 1, 2, \dots, n)$$

  where i is the index for each criterion.
- *Criteria weights* (w) – a MCDA problem requires information regarding the relative importance of each criterion. The relative importance can be represented in the form of weights which are usually normalised to one. Given that there are n criteria, a set of weight is defined as:

  $$w = (w_1, w_2, \dots., w_n \mid i = 1, 2, \dots, n)$$

  where i is the index for weights associated with the corresponding criterion and $\sum_{i=1}^{n} w_i = 1$.
- *Criteria scores* (x) – a MCDA problem requires information regarding the criteria performance with respect to each alternative. A criteria score (x_{ij}) reflect an alternative j performance on criterion i. A set of criteria score for an alternative is defined as (the index for the alternative is disregarded for simplicity):

  $$x = (x_1, x_2, \dots., x_n \mid i = 1, 2, \dots, n)$$
- *Decision matrix* (D) – a MCDA problem can be concisely denoted by a decision matrix for m alternatives and n criteria. The decision matrix D is a $m \times n$ matrix whose elements x_{ij} represent the performance level of criterion i (c_i) and alternative j, A_j.

A decision matrix can be defined as:

$$D = \begin{array}{c} \\ c_1 \\ c_2 \\ \vdots \\ c_n \end{array} \begin{array}{c} \begin{array}{cccc} A_1 & A_1 & \dots & A_m \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & & \vdots \\ x_{n1} & x_{n1} & \dots & x_{nm} \end{bmatrix} \end{array}$$

Thus far, the MCDA basic concepts including alternatives, criteria weights, criteria scores and decision matrix are introduced, but how all these relate to one another to produce a final performance outcome for each alternative is not discussed. To explain this, it is necessary to refer back to the chosen MCDA approach, *value measurement theory* as discussed in Section 2.4.3 p.35. One of the most common aggregation models adopted in the value measurement approach is the weighted average or more formally simple additive weighting (SAW) model. SAW has been pioneered in Australia as the Australian water industry has recently gone through a planning phase for long-term water strategies, hence the focus on the particular regions in this thesis (Water Services Association of Australia, 2009). Examples of this approach are the Gold Coast Waterfuture (Gold Coast Water, 2005), Gosford-Wyong Council Water Authority's Water Plan 2050 (Gosford-Wyong Council's Water Authority, 2006), and Water Corporation's Water Forever (Water Corporation, 2008). This thesis also adopted the SAW model as one of the underlying aggregation models (Eqn 4-1).

$$v_j(x) = \sum_{i=1}^{n} w_i x_{ij} \qquad \textbf{4-1}$$

where

$v_j(x)$ is the global value of alternative *j*

w_i is the weight associated with the importance of criterion *i* subject to $\sum_1^n w_i = 1$

x_{ij} is the score reflecting alternative A_j performance on criterion *i*.

The underlying aggregation model is also referred to as a *value function* in the value measurement theory (Keeney and Raiffa, 1976). A value function is a function that associates a number (or 'global value') to each alternative in such a way that alternative a is judged to be preferred to alternative b if $v(a) > v(b)$. A function, v is defined as a value function and can represent a DM's preference structure in two ways:

$$a \sim b \Leftrightarrow v(a) = v(b)$$

and $$a \succ b \Leftrightarrow v(a) > v(b)$$

A special feature of value measurement theory is that the inputs required for the preference model are critically related to the form of value function. Now with the MCDA problem and the underlying value function (SAW) defined more explicitly, it is easy to see that the preference model is concerned with identifying the following two components:

- *Criteria weights (w_i)* – representing the relative importance of each criterion
- *Criteria scores (x_{ij})* – representing the performance levels for each criterion.

The next two sections (Sections 4.2.1, 4.2.2) describe the development of the technique developed as part of this research to elicit criteria weights and criteria scores. A review of the existing methods to elicit criteria scores and criteria weights are presented in Appendix B.

4.2.1 Criteria weights

The concept: value trade-offs

To begin with, the author explains that criteria weights have a very specific algebraic meaning in the value measurement theory. The weights are scaling constants to render the different criteria to a common value scale (with minimum 0 and maximum 1). This is made possible because of a condition in the value measurement theory which requires that the criteria weights sum to unity ($\sum w_i = 1$) (Keeney and Raiffa, 1976). Since the sum of criteria weight is fixed to unity, the concept of *trade-off* is introduced.

A trade-off involves making a decision with full comprehension of sacrifices in some criteria performances in return for gaining performances in other criteria. To explain this more clearly, consider the weight parameter as a finite pool of resource (total value of the resource is 1) and a decision problem with two criteria c_1 and c_2. If a big portion of the resource (e.g. w_1 = 0.7) is assigned to c_1, this leaves a relatively much smaller portion of the resource (w_2 = 1–0.7 = 0.3) to assign c_2.

To make judgement about how much to give up on one criterion to achieve specific gain in another criterion is the essence of trade-offs. As discussed in Section 2.5.5 p.55, it is important to make trade-off judgement on the basis of specified criteria range, such that the consequences of the trade-offs are made explicit. To emphasise the importance of this, the term *value trade-off* is used to denote the importance of making trade-offs based on measurable criteria range.

It should be note that the trade-off made in the direct assignment method is different from the trade-off weight technique developed by Keeney described in Appendix B1. The full consequences of the actions were not quantified using Keeney's trade-off technique. This was confirmed from some of the pilot studies.

Technique to avoid range sensitivity: mitigation value trade-offs

In order to obtain value trade-offs that avoid range sensitivity, the author proposed an innovative technique *mitigation value trade-off* which utilised the concept of *mitigation* to describe the elicit value trade-off. Mitigation, according to the Oxford dictionary, is defined as "*making something bad less severe*". Making a mitigation value trade-off involves a given situation where there is a limited amount of money or resources to mitigate all the impacts as a result of a decision action. The consequences of the trade-offs involved are made explicit to the DMs by stating the various possible impacts for all criteria if different levels of mitigation are undertaken. DMs are given a choice to choose between different levels of mitigation for each criterion and there is a cost attached to mitigation level, "*What level of mitigation are you willing to accept for each criterion given the cost involved?*". The mitigation concept assists in the determination of value trade-offs by providing measurable global consequences; thus avoiding the range sensitivity issue. The procedure to elicit weight using the mitigated value trade-off technique is described as follows:

Step 1. Determine the number of mitigation level

Determine the number of mitigation level p $(p \in \mathbb{R})$ or the number on a point scale to represent the context domain. The most common scales are the 2-, 3- to 5-point scales (Dawis, 1987). The direction of scoring (e.g. for a 5-point scale whether 1 or 5 is high) should be consistent for all criteria. The construction of mitigation level is a variant form of a constructed qualitative scale as a means to describe the criteria range.

Step 2. Assign reference points and mitigated consequences

Let $m = (m_1, m_2, \dots, m_p)$ be real numbers that denote the mitigation values for a criterion where m is defined on the interval $m_i \in [0,100]$ and subject to the condition

$\sum_{r=1}^{p} m_r = 100$. The unity $\left(\sum_{r=1}^{p} m_r = 100\right)$ signifies the hypothetical sum of money given to the DMs to mitigate the impacts incurred by all the criteria. The unit can be in the form of $100,000, $100 million or 100 billion, depending on the scale of the decision problem.

Assign the reference points (worst and best end point) to the global scale (see Section 2.6.4 p.68 for the definition of a global scale). The worst and best point on the mitigation scale should be defined by the worst conceivable consequence $(m_1 = 0)$ and the ideal consequence $\left(m_p = 100\right)$, which could possibly occur on the particular criterion. The intermediate mitigated values are determined $m_r = r\left(\frac{100}{p}\right)$; $r = 2, \ldots, p-1$. For example, for a 5-point scale, the intermediate mitigated values are $m_2 = 25, m_3 = 50, m_4 = 75$. These mitigated values represent the price tags attached to each mitigation level so that each mitigation level reflects the resources required to mitigate the impact of the criterion. This allows the DMs to make the trade-offs between criteria using one commensurate scale.

Once the mitigated values are determined, the corresponding mitigation consequence with each *m* should be described. The worst scenario represents no mitigation at all, so the full impact that would be incurred by a criterion should be described. The best scenario represents the best management practice, indicating the best mitigation effort that could be afforded. By defining the range of mitigation to the global scale, all possibilities are defined and thereby avoid the range sensitivity issue.

Step 3. Elicited mitigation value

Mitigated value trade-off is a form of direct weight assignment with reference to a set of global measurable range or mitigated consequences. The total amount of resources available for mitigation is limited to a unit (e.g. $100 million, $100 billion). The DMs are asked to assign a mitigation value (0 – 100) to each criterion according to the level of mitigation that the DMs deem appropriate. Over-spending on one criterion can result in limited resources to mitigate other criteria.

The elicited mitigation values from the DMs directly reflect the importance of the criteria. The philosophy is that the more important a criterion is, the more the DMs would like to mitigate the impact associate with the criterion. Conversely, if an impact is not considered important, then the DMs willingness to mitigate it would also be reduced. The elicited mitigation values (m) are taken as the weights, $w \in [0,1]$ of the criteria as shown in Eqn 4-2 and the condition $\sum w_i = 1$ holds. It should be noted that the DMs are not restricted to select the mitigation value given by each level (e.g. 0, 25, 50, 75, 100 for the 5-point scale). The levels are there to provide guidance for the DMs.

$$w_i = \frac{m_i}{100} \tag{4-2}$$

For decision problems that are structured as a multi-level value tree, consideration must be given to weights at different levels of the tree. Criteria that share the same parent have weights that are normalised into a sum of unity. The weights (or mitigation values) can be assigned in a top-down or bottom up manner, refer to Appendix B1 for details on value tree weight assignment.

Example

An example of this mitigation value trade-off technique is given below. Five mitigation levels were chosen because this is a form of Likert scaling which is one of most widely accepted scale used in social science (Likert, 1932). These five levels are attached to a set of standardised price tags of \$0m, \$25m, \$50m, \$75m and \$100m in which each level of mitigation has its own specific consequence for different criteria.

Consider three criteria under the social category using the GCWF case study: (1) short-term construction impacts; (2) long-term impacts on local community; and (3) likelihood of community non-acceptance and the question, "*If you (the DM) are given a sum of \$100m to invest for mitigating the following stated impacts how much would you spend on each item of impact?*" Spending the \$100m on any one of the following impacts can mitigate or eliminate the problem entirely. The amount spent on mitigating each impact should sum up to \$100m. To assist DMs in making these judgements, the consequences of each mitigation level per impact are given in Table 4.2. A graphical format of the problem is illustrated in Figure 4.2 and a tabular format of the problem is presented in Table 4.1.

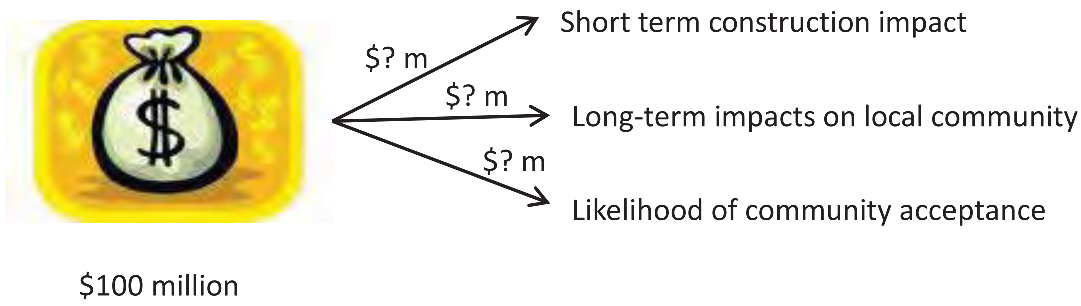


Figure 4.2 The mitigation value trade-off concept

Table 4.1 An example of eliciting value trade-off using mitigation: GCWF case study social criteria

Criteria	**Mitigation value trade-off (\$$m_i$ million)**	**Criteria weights** $w_i = m_i/100$
Short-term construction impact	m_1	w_1
Long-term impacts on local community	m_2	w_2
Likelihood of community non-acceptance	m_3	w_3
	$\sum m_i = 100$	$\sum w_i = 1$

Table 4.2 Consequences for each mitigation levels for the social criteria in the GCWF case study

		Worst ←		Mitigation level	→	Best
	Choice	**\$0m**	**\$25m**	**\$50m**	**\$75m**	**\$100m**
c_1	Short term construction impact (according to construction guideline)	Worst air/noise impact for 3 years, >10 ET† relocations	High air/noise impact for 3 years, > 5 ET relocations	Moderate air/noise impact for 3 years, >2 ET relocations	Minor air/noise impact for 3 years, no relocation	No impacts from construction at all
c_2	Long-term impacts on local community	Approx. 1000 ET will live next to recycling/ desalination facilities and disturbed by progressive brownfield pipelines construction	Approx. 750 ET will live next to recycling/ desalination facilities and disturbed by progressive brownfield pipelines construction	Approx. 500 ET will live next to recycling/ desalination facilities and disturbed by progressive brownfield pipelines construction	Approx. 250 ET will live next to recycling/ desalination facilities and disturbed by progressive brownfield pipelines construction	No disturbance on community - facilities located away from existing area and no brownfield pipelines
c_3	Likelihood of community acceptance	Non-acceptance of all 4 water sources (dam, recycle water & rainwater tanks and desal.)	Non-acceptance of 3 water sources (dam, recycle water & rainwater tanks)	Non-acceptance of 2 water sources (recycle water & rainwater tanks)	Non-acceptance of 1 water source (rainwater tanks)	Acceptance of all water sources
Ecosystem						
c_{4a}	Vegetation cleared	480 ha Sydney Olympic park land	360 ha equivalent to 2 Sydney Royal Botanical Garden	240 ha equivalent to Sydney Centennial Park	120 ha equivalent to Moore Park golf course	0 ha
c_{4b}	Flora and fauna	80 significant flora & fauna species affected	60 significant flora & fauna species affected	40 significant flora & fauna species affected	20 significant flora & fauna species affected	0 significant flora & fauna species affected
c_{4c}	Macroinvertebrate community (% of biodiversity left)	Biodiversity extremely impaired 20%-40% biodiversity left	Biodiversity severely impaired 40%-60% biodiversity left	Biodiversity significantly impaired 60%~80% biodiversity left	Biodiversity close to reference site 80%~100% biodiversity left	Biodiversity more than reference site 100%
c_{4d}	Marine organisms affected by brine discharge	4 marine organisms affected	3 marine organisms affected	2 marine organisms affected	1 marine organism affected	0 marina organism affected

		Worst ←		Mitigation level	→	Best
	Choice	$0m	$25m	$50m	$75m	$100m
Environment						
c_4	Loss of high value ecosystem	480 ha forest cleared / 80 flora & fauna species affected / 20–50% biodiversity left in waterways / 4 marine organisms affected	360 ha forest cleared / 60 flora & fauna species affected / 40–60% biodiversity left in waterways / 3 marine organisms affected	240 ha forest cleared / 40 flora & fauna species affected / 60–80% biodiversity left in waterways / 2 marine organisms affected	120 ha forest cleared / 20 flora & fauna species affected / 80–100% biodiversity left in waterways / 1 marine organisms affected	0 ha forest cleared / 0 flora & fauna species affected / 100% biodiversity left in waterways / 0 marine organisms affected
c_5	Greenhouse gas	1.2% increase in per capita tCO_2-eq (extra 70,000 cars on road)	1.02% increase in per capita tCO_2-eq (extra 60,000 cars on road)	0.85% increase in per capita tCO_2-e (extra 50,000 cars on road)	0.67% increase in per capita tCO_2-eq (extra 40,000 cars on road)	0.49% increase in per capita tCO_2-eq (extra 30,000 cars on road)
Technical						
c_6	Security of supply	Only relay on 1 source (dam)	Equal reliance on 2 sources (dam + RW‡)	Equal reliance on 3 sources (dam + RW + RWT‡)	Rely on 4 sources (dam + RW + RWT + desal‡) but higher emphasis on desal	Equal reliance on dam/RW/RWT/desal
c_7	Reliability of services	80%-100% of water demand is dependent on climate sensitive resources	60%-80% of water demand is dependent on climate sensitive resources	40%-20% of water demand is dependent on climate sensitive resources	20%-0% of water demand is dependent on climate sensitive resources	No dependence on climate sensitive water resources
c_8	Flexibility	Very low flexibility able to incorporate indirect potable reuse with > 10 yr delay	Low flexibility able to incorporate indirect potable reuse with 5–10 yr delay	Moderate flexibility able to incorporate indirect potable reuse with 2–5 yr delay	High flexibility able to incorporate indirect potable reuse with 1–2 yr delay	Very high flexibility able to incorporate indirect potable reuse with no delay
c_9	Risk (risk of cross contamination due to recycle water system)	Very high risk (less than 1 in 1000 person will be affected)	High risk (less than 1 in 5,000 person will be affected)	Moderate risk (less than 1 in 10,000 person will be affected)	Low risk (less than 1 in 50,000 person will be affected)	Very low risk (less than 1 in 100,000 person will be affected)

	Worst ←		Mitigation level		→ Best
Choice	**\$0m**	**\$25m**	**\$50m**	**\$75m**	**\$100m**
Overall					
Whole of life cost	Whole of life cost \$6.5b to meet the 466 ML/d* demand	Whole of life cost \$6.2b to meet the 466 ML/d demand	Whole of life cost \$5.9b to meet the 466 ML/d demand	Whole of life cost \$5.6b to meet the 466 ML/d demand	Whole of life cost \$5.3b to meet the 466 ML/d demand
Social	See the \$0m mitigation levels for c_1,c_2, c_3	See the \$25m mitigation levels for c_1,c_2, c_3	See the \$50m mitigation levels for c_1,c_2, c_3	See the \$75m mitigation levels for c_1,c_2, c_3	See the \$100m mitigation levels for c_1,c_2, c_3
Environment	See the \$0m mitigation levels for c_4,c_5	See the \$25m mitigation levels for c_4,c_5	See the \$50m mitigation levels for c_4,c_5	See the \$75m mitigation levels for c_4,c_5	See the \$100m mitigation levels for c_4,c_5
Technical	See the \$0m mitigation levels for c_6,c_7,c_8,c_9	See the \$25m mitigation levels for c_6,c_7,c_8,c_9	See the \$50m mitigation levels for c_6,c_7,c_8,c_9	See the \$75m mitigation levels for c_6,c_7,c_8,c_9	See the \$100m mitigation levels for c_6,c_7,c_8,c_9

† ET = equivalent tenant
‡ RW – Recycled water; RWT – Rainwater tanks; desal – Desalination
* ML/d – megalitre per day

4.2.2 Criteria scores

An important component of the preference modelling is to construct partial value functions to measure the relative performance level of each selected criterion. This process of assessing the value of performances of alternatives against the selected criteria (e.g. alternative a is preferred to b for a criterion if and only if $v_i(a) > v_i(b)$), can be referred to as the assessment of the *partial value function*, $v_i(a)$ or more commonly known as *normalisation*.

<u>The technique: mitigation normalising function (MnF)</u>

The author proposes a new normalising technique which utilises the mitigation value trade-offs elicited. *Normalising function f(x)* is a function that maps the raw criteria scores (x^*) to the normalised criteria scores $\left(x^* \longrightarrow x: f(x^*)\right)$ in such a way that the comparison between performances of different criteria are made possible. All the raw criteria scores are mapped to the unit interval [0,1]. This new normalising technique is based on Keeney and Raiffa's (1976) mid-point technique which is used to derive value functions[8]. Although value functions $v(x)$ and normalising functions $f(x^*)$ are two different types of functions, the philosophy behind Keeney and Raiffa's (1976) mid-point technique helps to construct normalising functions. The mitigation value trade-offs given by the DMs for each criterion are taken as midpoint values $x^*_{0.5}$ for defining the normalising functions. This is made possible because the philosophy behind the two concepts (mitigation value trade-offs and midpoint values) is rooted in Keeney's value trade-off concept:

- *Mitigation value trade-off* – the mitigation level represents a trade-off the DMs are willing to accept for a criterion
- *Midpoint value* – the midpoint value $(x^*_{0.5})$ reflects an acceptable trade-off such that the DMs value equally moving from the worst scenario (x^*_0) to the midpoint $(x^*_{0.5})$, and from the midpoint value $(x^*_{0.5})$ to the best scenario (x^*_1) (Figure 4.3). This midpoint can be interpreted as the performance level the DMs are willing to accept for that criterion.

[8] Value functions are the aggregation models which are used to represent DM's preference structure as discussed in Section 4.2. The outcome of a value function is a 'value' associated with an alternative to determine the preference order of alternatives. Normalising functions, in contrast, are partial value functions which are used as inputs for the value functions.

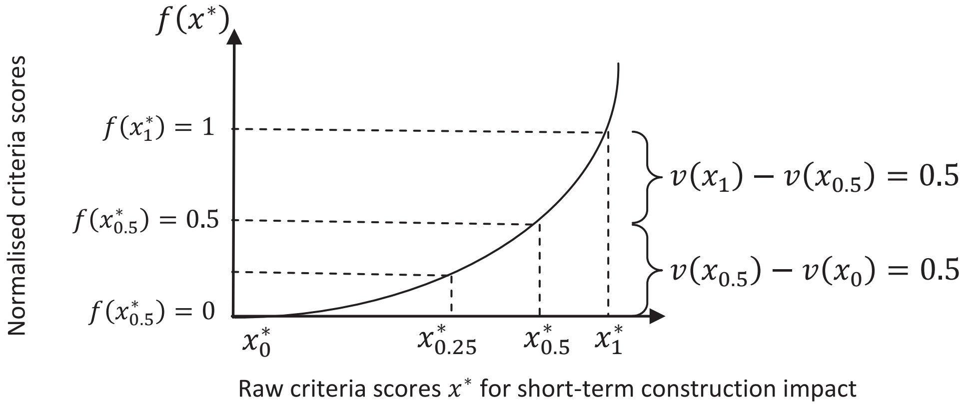


Figure 4.3 Midpoint technique for defining normalised functions

The following describes the procedure to derive a normalising function for a criterion using the author's proposed *mitigation value function*. The derived normalisation function using the following technique is called *mitigation normalising function* (MnF).

Step 1. Obtain mid value point $x_{0.5}$

Consider a real number interval describing the raw criterion score (x_0^*, x_1^*) for a criterion; where x_0^* is the value of a raw criterion score which corresponds to the worst normalised criteria score $v(x_0^*) = 0$ and x_1^* is the value of a raw criterion score which corresponds to the best normalised criteria score $v(x_1^*) = 1$. Find the raw criterion score or mid value point $x_{0.5}^*$ in between (x_0^*, x_1^*), in which the normalised criteria score $v(x_{0.5}^*)$ is equal to 0.5. The mitigation value trade-off given by the DM for a criterion according the technique introduced in Section 4.2.10 p.126 is taken as the midpoint value $x_{0.5}^*$.

Step 2. Midvalue splitting

To refine the normalising function, midpoint values such as $x_{0.25,}^*$ $x_{0.75}^*$ or additional points x_k^* can be obtained where $k = (0, 1, 0.5, 0.75, 0.25, \ldots.)$. These midpoint values $x_{0.25,}^*$ $x_{0.75}^*$ can be determined by asking the DM what is the midpoint value between $(x_0^*, x_{0.5}^*)$ and $(x_{0.5}^*, x_1^*)$. This again requires the mitigation value trade-off technique to elicit the midpoints. To explain the procedure, an example from the GCWF case study is used. Suppose a DM has assigned a mitigation value trade-off of \$75m $(m = x_{0.5}^* = 75)$ to the criterion 'short-term construction impact' and now the facilitator is interested to find $x^*_{0.25}$. The scale of mitigation level for short-term construction impact is shown in Table 4.3.

Table 4.3 Mitigation levels for short-term construction impact

		Worst ⟵		Mitigation level	⟶	Best
	Criteria	**$0m**	**$25m**	**$50m**	**$75m‡**	**$100m**
1	Short term construction impact (as per construction guidelines)	Worst air/noise impact for 3 years, >10 ET† relocations	High air/noise impact for 3 years, > 5 ET relocations	Moderate air/noise impact for 3 years, >2 ET relocations	Minor air/noise impact for 3 years, no relocation	No impacts from construction at all

† ET = equivalent tenant
‡ $m = x^*_{0.5}$

By default, x^*_0 is represented by the worst scenario — worst air/noise impact for 3 years, >10 Equivalent Tenant (ET) relocations — and x^*_1 is represented by the best scenario — no impacts at all. The mitigated scenario $x^*_{0.5}$ is represented by the chosen $75m scenario (minor air/nose impact for 3 years, and no relocation) (Table 4.4). The facilitator can use the following technique to elicit $x^*_{0.25}$:

"You (the DM) have specified that you are willing to spend $75m to mitigate the short-term construction impact. This value signifies that you are willing to spend the same amount of money ($75m) to move from the worst scenario x^*_0 to the mitigated scenario $x^*_{0.5}$, and from the mitigated scenario to the best scenario x^*_1. Let's consider a midpoint between the worst scenario x^*_0 to the mitigated scenario $x^*_{0.5}$. Say now your best scenario is replaced by the mitigated scenario and the maximum that you can spend on mitigation is $75m. How much would you spend on mitigating short-term construction impact (between $0m and $75m) bearing in mind that the maximum possible you can achieve is your previously chosen mitigated scenario (minor air/nose impact for 3 years with no relocation?)"

Table 4.4 Mitigation levels for short-term construction impact from the GCWF case study (2)

		Worst ◄	Mitigation level		► Best
	Criteria	**\$0m**	**\$25m**	**\$50m‡**	**\$75m**
1	Short term construction impact (as per construction guidelines)	Worst air/noise impact for 3 years, >10 ET† relocations	High air/noise impact for 3 years, > 5 ET relocations	Moderate air/noise impact for 3 years, >2 ET relocations	Minor air/noise impact for 3 years, no relocation

† ET = equivalent tenant

‡ $m = x^*_{0.25}$

Step 3. Construct normalised function $f(x^*)$

The function for criterion *x* is the curve that passes through the points $\left(x^*_k, f(x^*_k)\right)$ for $k = (0, 1, 0.5, 0.25)$. The relationship between mitigation trade-off value, criteria weights and midpoint value can be described as follows (Eqn 4-3):

$$\frac{m}{100} = w = x^*_{0.5} \quad \textbf{4-3}$$

This is another innovation introduced as part of this research in which the mitigation value trade-off is associated with the normalising function. The author differentiates this method as *mitigated normalising function* (MnF). An implication of this relationship is that the importance of the criteria implicitly influences the normalised criteria scores obtained by the normalising functions. This overcomes the issues of over-emphasising the better performing criteria and reducing the importance of the poorer performing criteria. This issue is typically associated with the common approach such as min-max approach which is discussed earlier in the same section. The influence of linking the criteria importance to the criteria score is such that:

- a criterion with high importance implies that the requirement placed on criterion is stricter, thus it is more difficult to achieve higher normalised criteria score (Figure 4.4 (a)); and
- a criterion with low importance implies that the requirement placed on criterion is looser, thus it is easier to achieve higher normalised criteria scores. The logic is that given a criterion is of lower importance, it does not matter even though the performance score for the criterion is very high and vice versa (Figure 4.4 (b)).

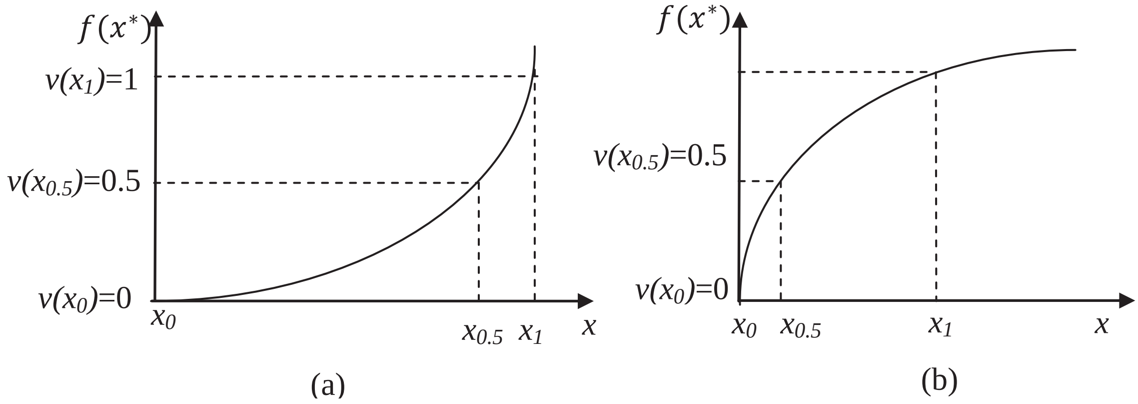


Figure 4.4 Influence of criteria importance on normalised criteria scores (a) high criteria importance (lower criteria scores) (b) low criteria importance (higher criteria scores)

4.2.3 Gold Coast Waterfuture case study

To illustrate the two procedures described above: (1) mitigation value trade-offs (to elicit criteria weights) and (2) mitigated normalising functions (to standardise criteria scores), the two procedures are applied to the GCWF case study. As a brief recap, the elicitation of mitigation value trade-offs determines criteria weight directly. The normalising functions are also indirectly derived based on the elicited mitigation value trade-offs. The raw criteria scores are normalised by using the mitigated normalising function to obtain normalised criteria scores. Together with the criteria weights and normalised criteria scores identified, the tasks of preference modelling is complete. This section is divided into two parts: **Part A** showcases the method of determining criteria weights through the elicited mitigation value trade-offs; **Part B** illustrates the process of determining normalising functions and normalised criteria scores.

Prior to describing the two parts, the raw criteria scores for the GCWF case study are first introduced. In the GCWF case study, the criteria scores were assessed by the GCWF Advisory Committee. However, the criteria scores reflected only the view of the GCWF committee and were not necessarily agreed with by the DMs participating in this research study. Therefore to accommodate this issue, the participants were allowed to modify the scores based on their own judgements, if this seemed appropriate; but they could also choose to accept the raw criteria scores. The raw criteria scores $\left(x_{ij}^{*}\right)$ for the GCWF case study are presented in Table 4.5. They were extracted from the GCWF strategy assessment (Gold Coast Water, 2005), in which the raw criteria scores were assigned to the five strategies (A, B, C, D, E) as described in Chapter 3. The data presented in Table 4.5 in essence is the decision matrix *D* (see Section 4.2). Explanations for the scores are provided in Appendix E4. A copy of this was given to the participants to assist them in the judgement of modifying or accepting the raw criteria scores.

Table 4.5 Decision matrix with raw criteria score (x_{ij}^{*})s for the GCWF case study (Gold Coast Water, 2005)

Criteria	Water Strategies for Gold Coast Scores				
Social	**A**	**B**	**C**	**D**	**E**
Short term construction impact (c_1)	62	64	70	74	68
Long-term impacts on local community (c_2)	74	68	74	68	58
Likelihood of community acceptance (c_3)	62	62	86	66	62
Ecosystem	**A**	**B**	**C**	**D**	**E**
Forest (c_{4a})	1	99	88	99	88
Flora and fauna (c_{4b})[9]	18	79	60	63	39
Macro-invertebrates (c_{4c})[8]	60	90	70	80	80
Marine organisms (c_{4d})[8]	80	60	60	60	80
Environmental	**A**	**B**	**C**	**D**	**E**
Loss of high value ecosystem (c_4)	44	68	68	76	78
Greenhouse gas (c_5)	67	18	37	47	74
Technical	**A**	**B**	**C**	**D**	**E**
Security of supply (c_6)	38	34	34	50	56
Reliability (c_7)	58	76	64	62	72
Flexibility (c_8)	63	53	63	60	67
Risk (c_9)	56	69	70	63	52
Overall	**A**	**B**	**C**	**D**	**E**
Economic	51	83	75	49	39
Social	66	65	77	69	63
Environment (includes ecosystem)	56	43	53	62	76
Technical	54	58	58	59	62

Notice that the criterion for economic is group under the overall section alongside with the overall social, environmental and technical criteria. This arrangement was made because there was only one economic criterion, therefore, economic was grouped together with the other three main criteria groups.

Part A. Determination of criteria weights

The purpose of this section is to obtain the criteria weights for the GCWF case study using the mitigation value trade-off technique introduced in Section 4.2.10 p.126. Later

[9] The scores for the criteria fauna and flora, macro-invertebrates and marine organisms affected are derived from the Environmental Impact Statements from Hinze Dam upgrade and desalination. The same applied to the overall social, environmental and technical raw scores.

in Section 4.3 different types of criteria weights are introduced[10]. Here, the author demonstrates the procedure to derive criteria weights which builds a foundation for the different types of criteria weights to be introduced later.

The mitigation value trade-off technique was applied in the GCWF case study to first determine criteria weights using Eqn 4-2. For each criterion, a mitigation value trade-off was elicited from each DM. In applying the midpoint technique to derive value functions for the GCWF case study, only one midpoint value was obtained per criterion (which was the mitigation value trade-off) because this was the most efficient way to derive value functions in a limited timeframe. For more accurate assessment of the normalising functions, the procedure can be repeated by finding extra mid-value points such as $x^*_{0.25}$ and $x^*_{0.75}$. The criteria weights for the participations in the water experts (E1, E2, E3, E4) and the water managers (M1, M2) are presented in Table 4.6[11]. The criteria weights elicited from the water users (S1 – S10) are presented in Table 4.7 and the water users (S1 – S10) in Table 4.8.

It was observed that some of the participants preferred to rank rather than giving mitigation value trade-offs for criteria for various reasons (for ease or simply because they found it difficult to assign trade-off in numerical values). To overcome this, standard mitigation values were allocated according to the ranking positions of the criteria (Rank 1 w = 0.4, Rank 2 w = 0.3, Rank 3 w = 0.2 and Rank 1 w = 0.1).

[10] The purpose of having different types of criteria weights (crisp criteria weight, fuzzy criteria weights, Shapley index and interaction index) is to apply different aggregation models for solving the two identified shortcomings (judgement uncertainty and criteria interaction).

[11] Note that there are no mitigation value trade-offs (criteria weights) for water manager M2. This is because the interview duration with the water manager M2 was limited to an hour, there was insufficient time to complete the entire workbook. Hence, the water manager M2 only completed the sections on ecosystem, environment and technical criteria..

Table 4.6 Criteria weights for the water experts (E1–E4) and water managers (M1–M2)

	Water experts and managers					
Social	**E1**	**E2**	**E3**	**E4**	**M1**	**M2**
c_1	0.2	0.2	0.4	0.4	0.25	-
c_2	0.5	0.5	0.4	0.3	0.25	-
c_3	0.3	0.3	0.2	0.3	0.5	-
Ecosystem	**E1***	**E2***	**E3***	**E4***	**M1**	**M2**
c_{4a}	0.2	0.4	0.4	0.2	0.4	0.25
c_{4b}	0.3	0.2	0.3	0.4	0.4	0.25
c_{4c}	0.4	0.3	0.2	0.1	0.2	0.5
c_{4d}	0.1	0.1	0.1	0.3	0	0
Environment	**E1**	**E2**	**E3**	**E4**	**M1**	**M2**
c_4	0.4	0.85	0.3	0.6	1	0.2
c_5	0.6	0.15	0.7	0.4	0	0.8
Technical criteria	**E1***	**E2***	**E3***	**E4***	**M1**	**M2**
c_6	0.2	0.4	0.3	0.4	0.7	0.5
c_7	0.4	0.2	0.2	0.3	0.25	0.5
c_8	0.3	0.2	0.1	0.1	0	0
c_9	0.1	0.1	0.4	0.2	0	0
Economic and others	**E1**	**E2**	**E3**	**E4**	**M1**	**M2**
Economics	0	0.05	0.1	0.1	0	-
Social	0.3	0.25	0.3	0.2	0.1	-
Environment	0.4	0.3	0.3	0.35	0.2	-
Technical	0.3	0.4	0.3	0.35	0.7	-

Note* These participants used ranking instead of mitigation value trade-offs to evaluate the importance of the criteria under the prescribed criteria group. This happened because the interview with water experts E1, E2, E3 and E4 took place during the early phase of the main interview. Ranking in the ecosystem and technical sections was the preferred method of deriving weights for interacting criteria. This was corrected in the subsequent interviews. Hence standard mitigation values were allocated according to the ranking positions of the criteria (Rank 1 w = 0.4, Rank 2 w = 0.3, Rank 3 w = 0.2 and Rank 1 w = 0.1).

Averages of the criteria weights were taken for the water experts and manager group. They are presented graphically in Figure 4.5.

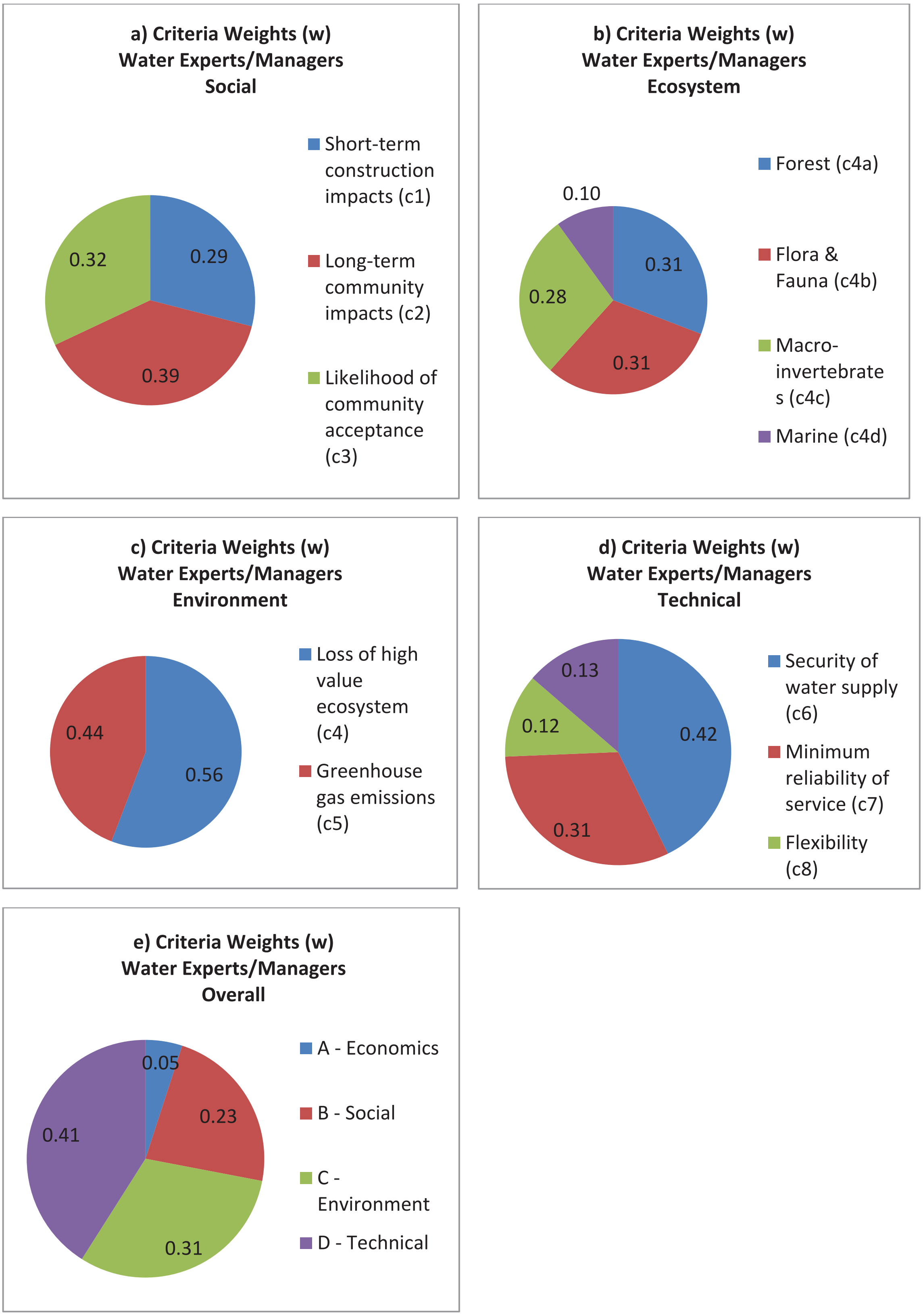


Figure 4.5 Average criteria weights given by water experts/water managers for (a) social (b) ecosystem (c) environment (d) technical (e) overall

Table 4.7 Criteria weights for the water users (S1–S10)

Criteria	Water users									
Social	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
c_1	0.35	0.2	0.3	0.4	0.2	0.2	0.5	0.25	0	0.25
c_2	0.5	0.6	0.6	0.4	0.3	0.6	0.5	0.45	0.5	0.5
c_3	0.15	0.2	0.1	0.2	0.5	0.2	0	0.3	0.5	0.25
Ecosystem	**S1**	**S2**	**S3**	**S4**	**S5**	**S6***	**S7***	**S8***	**S9**	**S10**
c_{4a}	-	-	0.5	0.4	0.3	0.3	0.1	0.1	0.5	0.5
c_{4b}	-	-	0.2	0.2	0.3	0.2	0.3	0.4	0.25	0.25
c_{4c}	-	-	0.2	0.2	0.2	0.1	0.2	0.3	0.25	0.25
c_{4d}	-	-	0.1	0.2	0.2	0.4	0.4	0.2	0	0
Environment	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
c_4	0.7	0.6	0.4	0.6	0.6	0.5	0.8	0.4	1	0.25
c_5	0.3	0.4	0.6	0.4	0.4	0.5	0.2	0.6	0	0.75
Technical	**S1**	**S2**	**S3**	**S4**	**S5***	**S6***	**S7***	**S8***	**S9**	**S10**
c_6	0.1	0.1	0.1	0.2	0.3	0.2	0.4	0.3	0.5	0.25
c_7	0.3	0.25	0.1	0.2	0.4	0.3	0.3	0.1	0	0.5
c_8	0.1	0.25	0.1	0.2	0.1	0.1	0.1	0.2	0.25	0
c_9	0.5	0.4	0.7	0.4	0.2	0.4	0.2	0.4	0.25	0.25
Overall	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Economics	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0	0.15
Social	0.45	0.2	0.15	0.2	0.1	0.1	0.3	0.2	0.25	0.1
Environment	0.35	0.25	0.3	0.6	0.6	0.4	0.2	0.4	0	0.5
Technical	0.1	0.25	0.45	0.2	0.2	0.4	0.4	0.3	0.75	0.25

Note* These participants used ranking instead of mitigation value trade-offs to evaluate the importance of the criteria under the prescribed criteria group. Hence standard mitigation values were allocated according to the ranking positions of the criteria (Rank 1 W = 0.4, Rank 2 W = 0.3, Rank 3 W = 0.2 and Rank 1 W = 0.1). The same reasoning as explained in Table 4.6 applies.

Table 4.8 Criteria weights for the water users (S11–S20)

Criteria	Water users									
Social	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
c_1	0.5	0.25	0.25	0.25	0.25	0.375	0	0	0	0.15
c_2	0.25	0.25	0.25	0.25	0.25	0.375	0.5	0.5	0	0.5
c_3	0.25	0.5	0.5	0.5	0.5	0.25	0.5	0.5	1	0.35
Ecosystem	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
c_{4a}	0.5	0	0	0	0.125	0.4	0.25	0.5	0	0.35
c_{4b}	0.25	0.5	0.5	0.5	0.5	0.3	0	0.5	0.25	0.35
c_{4c}	0.25	0.5	0.5	0.5	0.25	0.2	0.5	0.25	0.25	0.25
c_{4d}	0	0	0	0	0.125	0.1	0.25	0	0.5	0.05
Environment	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
c_4	0.75	1	1	1	0.6	0.4	0.5	0.75	0.5	0.45
c_5	0.25	0	0	0	0.4	0.6	0.5	0.25	0.5	0.55
Technical	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
c_6	0.25	0.25	0.25	0.5	0.5	0.4	0.5	0.5	0.25	0.35
c_7	0.25	0.25	0	0	0.25	0.3	0.25	0.25	0.25	0.3
c_8	0	0.25	0.25	0.25	0.125	0.15	0.25	0.25	0.25	0.2
c_9	0.5	0.25	0.5	0.25	0.125	0.15	0	0	0.25	0.15
Overall	**S11**	**S12**	**S13**	**S14**	**S15**	**S16**	**S17**	**S18**	**S19**	**S20**
Economics	0.1	0	0	0	0.1	0.1	0	0	0	0.25
Social	0.25	0.25	0.25	0.05	0.2	0.4	0.5	0.25	0.25	0.15
Environment	0.4	0.25	0.25	0.75	0.4	0.3	0.25	0.5	0.5	0.25
Technical	0.25	0.5	0.5	0.2	0.2	0.2	0.25	0.25	0.25	0.35

Averages of the criteria weights were taken for the water experts and manager group. They are presented graphically in Figure 4.6

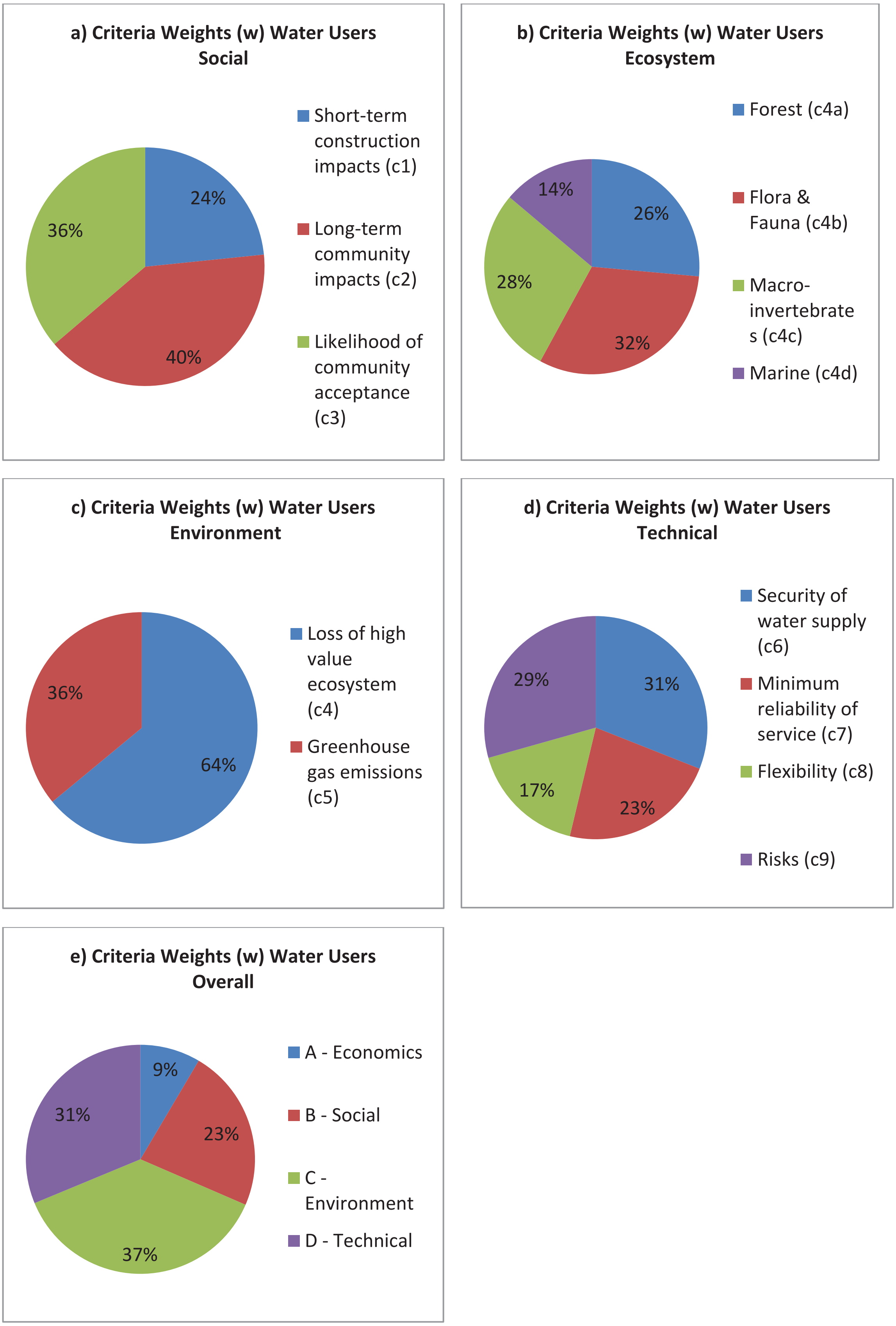


Figure 4.6 Average criteria weights given by water users for (a) social (b) ecosystem (c) environment (d) technical (e) overall

Part B. Determination of normalising functions types

The purpose of this section is to apply the mitigation value trade-off technique (introduced in Section 4.2.10 p.126) to determine the types of mitigated normalising functions (MnF) using the GCWF case study. In the GCWF, there was only one midpoint value obtained for each criterion per participant, the author standardised five possible mitigated normalising functions for all criteria $f_t(x^*)$ where t is the index for the five functions (t = 1, 2, 3, 4, 5). $f_1(x^*)$, $f_2(x^*)$, $f_3(x^*)$, $f_4(x^*)$ and $f_5(x^*)$ are conveniently denoted as (mitigated normalising functions) MnF1, MnF2, MnF3, MnF4 and MnF5. This treatment was applied specifically for the GCWF case study because there was insufficient time to obtain unique mitigated normalising functions for all criteria and for each individual DM. Unique mitigated normalising functions can be obtained if multiple midpoints are elicited from the DMs as suggested in Part A in the previous section.

In this section, in order to determine which mitigated normalised function applies, any mitigation value trade-off (m) that fell in the mitigation value trade-off range outlined in Table 4.9 had the corresponding midpoint value ($x^*_{0.5}$) and was assigned with the corresponding MnF type. Based on the m elicited from the participants (Table 4.6, Table 4.7, Table 4.8) the types of normalising value function were determined. The determined mitigated normalising function types in the GCWF case study are presented in Appendix F1.

Table 4.9 Ranges of mitigation value trade-off for selection of midpoints and MnF types

Value functions	MnF1	MnF2	MnF3	MnF4	MnF5
Value function range based on mitigation value trade-off (m)	0–24	25–41	42–59	60–75	76–100
Midpoint value ($x^*_{0.5}$)	0	25	50	75	100

Thus far, Section 4.2 outlines the basic elicitation technique to obtain criteria weights and normalised criteria scores. The next section (Section 4.3) outlines four different preference models to combine criteria weights and normalised criteria scores. Four preference models were investigated to account for the two shortcomings associated with the use of MCDA: judgement uncertainty and criteria interaction.

4.3 Preference modelling: four cases

The purpose of this section is to provide details on the four preference models with different value functions (underlying aggregation models). The four preference models are briefly introduced in Section 3.3.1 p.74. The outputs of these four preference models are four different ways of aggregating criteria weights and normalising criteria scores (elicited from Section 4.2). The aggregated results from the four cases are compared to each other to consider the influence of the two shortcomings identified with MCDA use (judgement uncertainty and criteria interaction). The results of the aggregated results are presented in Chapter 5. The four models are:

Case 1. Assume without judgement uncertainty and criteria interaction – base case

Case 2. Assume with judgement uncertainty

Case 3. Assume with criteria interaction

Case 4. Assume with judgement uncertainty and criteria interaction.

The differentiation between the four cases is not straightforward. The categorisation of these four cases is summarised in Table 4.10. Each case is characterised by a different value function and descriptors for criteria weights and normalised criteria scores.

Table 4.10 Four cases of preference models for investigation

	Description	Value function	Descriptor for criteria weights and normalised criteria scores
Case 1	Without judgement uncertainty and criteria interaction	Averaging family	**Part A:** Crisp criteria weights **Part B:** Crisp criteria scores
Case 2	With judgement uncertainty	Averaging family	**Part A:** Fuzzy criteria weights **Part B:** Fuzzy criteria scores
Case 3	With criteria interaction	Choquet integral	**Part A:** Shapley value, Interaction index } Crisp criteria weights **Part B:** Crisp value function / criteria scores
Case 4	With judgement uncertainty and criteria interaction	Choquet integral	**Part A:** Shapley value, Interaction index } Crisp criteria weights **Part B :** Fuzzy criteria scores

To explain these four cases more clearly and how they address the two shortcomings, a summary is given in the following.

Value functions – there are two main types of value functions considered here: the family of averaging aggregation models and the Choquet integral.

- *Family of averaging aggregation models:* averaging is one of the most common ways of aggregating multiple inputs. Here, the author is referring to a family aggregation models which share the same property (aggregated score not above or below the inputs) and not referring specifically to only the classic averaging operator $\left(\frac{1}{n}\sum x\right)$. Averaging aggregation treats all criteria as independent entities and therefore, it does not consider criteria interaction. Typical averaging aggregation operators are SAW, median, harmonic average and geometric average.
- *Case 1 and Case 2:* it was assumed that no criteria interaction was involved. Therefore, the family of averaging aggregation models was applied.
- *Choquet integral:* is an aggregation operator that considers criteria interaction. Details about this aggregation operator are introduced in Section 2.6.30 p.66 and Appendix D2.
- *Case 3 and Case 4:* it was assumed that criteria interaction was involved. Therefore, the Choquet integral was applied.
- *Criteria weights:* for the Choquet integral, criteria weights are not expressed as weights in the same sense as in the conventional SAW. In the Choquet integral, there are two parameters to express the relative importance of criteria: *Shapley index* and *interaction index*[12]. The Shapley index represents the contribution of a criterion to the overall decision and the interaction index is a measure of the positive or negative interaction between criteria. For simplicity, together these two parameters are referred to as 'criteria weights' in the sense that they represent the relative importance of criteria.

Descriptors for criteria weights and normalised criteria scores – there are two different types of descriptors — crisp and fuzzy sets. A crisp set refers to a set of elements that are represented by scale real numbers. A fuzzy set refers to a set of elements in which membership of an element is measured by a function that attempts to describe uncertainty. For more details about the differences between the two types of set, refer to Appendix D.

- *Crisp set* – in Case 1 and Case 3, it was assumed that no judgement uncertainty was involved. Therefore, the criteria weights and criteria scores are defined by crisp sets.

[12] See Appendix D2 for description of these two indices.

- *Fuzzy set* – in Case 2 and Case 4, it was assumed that judgement uncertainty was involved. To account for the judgement uncertainty, the criteria scores and criteria weights were defined as fuzzy sets.

The following sections (Sections 4.3.1, 4.3.2, 4.3.3, 4.3.4) describe the application of the four cases to the case study individually, in which each case is divided into two parts:

- **Part A. Criteria weights** details the derivation of either crisp or fuzzy criteria weights depending on whether the case considered judgement uncertainty or not
- **Part B. Mitigation normalising Function (MnF) and normalised criteria scores** details the derivation of either crisp or fuzzy MnF to determine the corresponding normalised criteria scores. The choice of crisp or fuzzy MnF depends on whether the case considered criteria interaction or not.

4.3.1 Case 1. Without judgement uncertainty and criteria interaction

In this case, the following assumptions were made:

- preferential independency between criteria was assumed which enabled the family of averaging aggregation operators to be adopted as the value functions
- judgement uncertainty was not assumed and therefore crisp criteria weights and normalised crisp criteria scores were determined.

This case represented the base case for the other three cases to compare with because this type of preference model is typically adopted to aid urban water management decisions. The procedure to obtain criteria weights is first described in Part 0 and normalised criteria scores in Part 0. Examples are given in Part 0 to illustrate the two procedures. Two outputs from this case were (Figure 4.7):

- crisp criteria weights
- normalised crisp criteria scores.

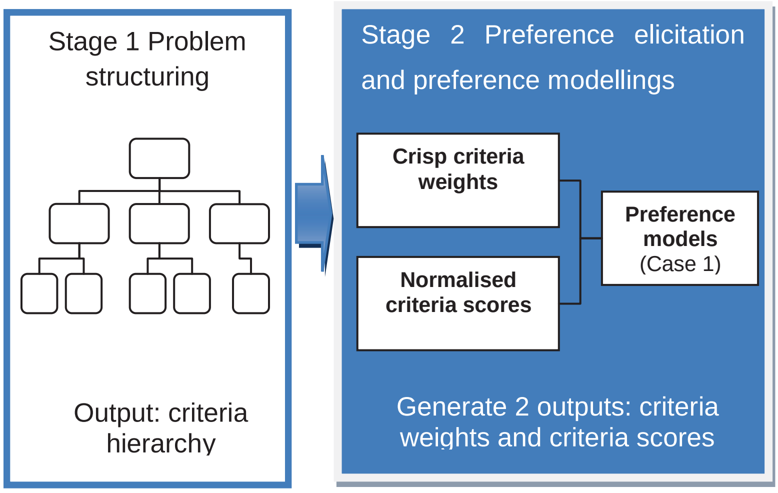


Figure 4.7 Decision support approach for case 1

Part A. Crisp criteria weights

The crisp criteria weights were obtained based on the mitigated value trade-offs technique as described in Section 4.2.10 p.126. The elicited mitigation value trade-offs were converted into criteria weights by using Eqn 4-2. The criteria weights obtained from the participants in the GCWF case study are shown in Table 4.6, Table 4.7 and Table 4.8.

Part B. Crisp MnF and normalised criteria scores

This section draws on the mitigation normalising function technique introduced in Section 4.2.2 p.133 to determine the partial value functions $f(x^*)$ accordingly. As stated previously, there were five standardised value functions (MnF1, MnF2, MnF3, MnF4 and MnF5) developed for the case study (Table 4.9). These five value functions were related to the five mitigation levels for determining the criteria scores. The five mitigation levels were based on the five Likert scaling system, hence the reason for the five value functions. In this case, the five MnF were fed by crisp criteria scores in this case, therefore they were called crisp MnF. The normalised criteria scores are referred to as normalised crisp criteria scores. The results obtained for the normalised crisp criteria scores for the GCWF case study are presented in Appendix F2.

The five crisp MnF were determined individually by connecting curves that pass through the respective elicited midpoints $\left(x_k^*, f(x_k^*)\right)$ (A, B, C, D, E, F) and also the end points (O, P). For example, the midpoint for MnF1 was $A(0,0.5)$ and there as only one end point which is $(0,1)$. The curve for MnF1 was constructed by passing a line through point A and P. The points required to be passed through for each MnF are illustrated in Figure 4.8 and presented in Table 4.11.

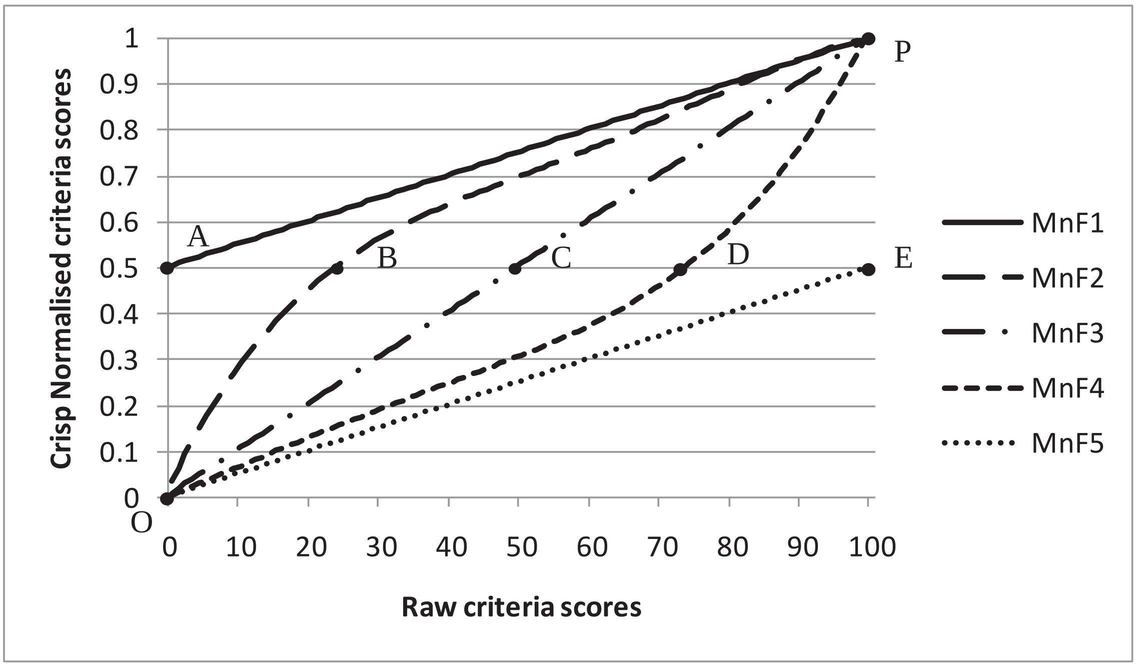


Figure 4.8 Five crisp MnF

Table 4.11 End points and midpoints for the five crisp MnF

	Point 1 $(x_0^*, f(x_0^*))$	**Point 2** $(x_{0.5}^*, f(x_{0.5}^*))$	**Point 3** $(x_1^*, f(x_1^*))$
MnF1	-	A (0, 0.5)	P (100, 0)
MnF2	O (0, 0)	B (25, 0.5)	P (100, 0)
MnF3	O (0, 0)	C (50, 0.5)	P (100, 0)
MnF4	O (0, 0)	D (75, 0.5)	P (100, 0)
MnF5	O (0, 0)	E (100, 0.5)	-

For MnF1, MnF3 and MnF5, the curves were simply linear lines that pass through points the *(A, P)*, *(O, C, P)*, and *(O, E)* respectively (Figure 4.8). For MnF2 and MnF4, the curves were not linear. To determine MnF2 and MnF4, the curve fitting toolbox from MATLAB was used. Polynomials to the fourth degree were used to smooth the curves because that gave the best fitting. The following equations (Eqn 4-4 to 4-9) were obtained from the curve fitting and characterise the five crisp MnF respectively:

MnF1 $$f_1(x^*) = 0.005x^* + 0.5 \quad \textbf{4-4}$$

$$f_2(x^*) = -0.061y^4 + 0.134y^3 - 0.07y^2 + 2.376y + 0.659 \quad \textbf{4-5}$$

MnF2 $$y = \frac{x^* - 43.75}{38.528} \quad \textbf{4-6}$$

MnF3 $$f_3(x^*) = 0.01x^* \quad \textbf{4-7}$$

MnF4 $$f_4(x^*) = 1.642E^{-8}(x^*)^4 - 1.696E^{-6}(x^*)^3 + 4.57E^{-5}(x^*)^2 + 6E^{-3}(x^*) - 9.526E^{-5} \quad \textbf{4-8}$$

MnF5 $$f_5(x) = 0.005x^* \quad \textbf{4-9}$$

Case 1. Example

Consider the four technical criteria (security of supply, reliability, flexibility and risks) from the GCWF case study. The mitigation value trade-offs given by a water manager (M2) in the case study are used here as an example (Table 4.12).

Part A. Crisp criteria weights

The mitigation value trade-offs given by M2 for the four criteria were m_6 = 50, m_7 = 50, m_8 = 0 and m_9 = 0. Therefore, the corresponding crisp criteria weights were m_6 = 0.5, m_7 = 0.5, m_8 = 0 and m_9 = 0. Refer back to Table 4.9 for the assignment of MnF types based on the ranges of mitigated value trade-off.

Table 4.12 Mitigation value trade-offs for technical criteria given by water manager M2

Technical criteria	Mitigation value trade-offs given by M2 (m_i)	Ranges of mitigation value trade-off[13] (m_i)	Crisp criteria weights ($w_i = m_i/100$)	Mitigated normalising function type
Security of supply (c_6)	50	42 – 59	0.5	MnF3
Reliability (c_7)	50	42 – 59	0.5	MnF3
Flexibility (c_8)	0	0 – 24	0	MnF1
Risks (c_9)	0	0 – 24	0	MnF1

Part B. Crisp MnF and normalised criteria scores

The types of value functions were assigned according to the value function ranges (column 4 in Table 4.13). For example, the mitigation value trade-off for security of

[13] The mitigation value trade-off range is extracted from Table 4.14.

supply/reliability ($m_6 = m_7 = 50$) fell in the range for MnF3 (m_{MnF3} = 42–59 see Table 4.12 and Table 4.9) and the mitigation value trade-off for flexibility/risks ($m_8 = m_9 = 50$) fell in the range for MnF1 (m_{MnF3} = 0–24 see Table 4.9 and Table 4.12). Therefore, the normalising function for security of supply and reliability were MnF3 and the normalising functions for flexibility and risks were both MnF.

The raw criteria scores for the four technical criteria are presented in Table 4.13. They are extracted from Table 4.5. To obtain the normalised criteria scores, the raw criteria scores were used as inputs in Eqn 4-4 and 4-7 for MnF1 and MnF3 respectively. The obtained normalised criteria scores are shown in Table 4.13.

Table 4.13 Original and normalised technical crisp criteria scores

Technical raw scores	**Raw criteria scores (x_i^*)**					**Normalised crisp criteria scores (x_i)**				
Strategies	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Security of supply (c_6)	38	34	34	50	56	0.38	0.34	0.34	0.50	0.56
Reliability (c_7)	58	76	64	62	72	0.58	0.76	0.64	0.62	0.72
Flexibility (c_8)	63	53	63	60	67	0.82	0.77	0.82	0.80	0.84
Risks (c_9)	56	69	70	63	52	0.78	0.85	0.85	0.82	0.76

Take strategy A as an example, the normalised crisp scores for the four criteria are derived as follows:

Using Eqn 4-7 the normalised crisp criteria score for security of supply is:

$$f_3(38) = 0.01(38) = 0.38$$

Using Eqn 4-7 the normalised criteria score for reliability is:

$$f_3(58) = 0.01(58) = 0.58$$

Using Eqn 4-4 the normalised criteria score for flexibility is:

$$f_1(63) = 0.005(63) + 0.5 = 0.82$$

Using Eqn 4-4 the normalised criteria score for risks is:

$$f_1(56) = 0.005(56) + 0.5 = 0.78$$

As a brief summary, this case has obtained for the GCWF case study the following:

- crisp criteria weights
- defined crisp mitigated normalising functions (MnF)
- normalised crisp criteria scores.

4.3.2 Case 2. With judgement uncertainty

In this case, the following assumptions were made:

- preferential independency between criteria was assumed which enabled the family of averaging aggregation operators to be adopted as the value functions
- judgement uncertainty was assumed and therefore fuzzy criteria weights and fuzzy criteria scores were determined.

This section explains how fuzzy set theory is incorporated in the preference model to account for judgement uncertainty by obtaining (Figure 4.9):

- fuzzy criteria weights
- fuzzy criteria scores.

(Fuzzy set theory and the definitions for fuzzy numbers are introduced in Appendix D1).

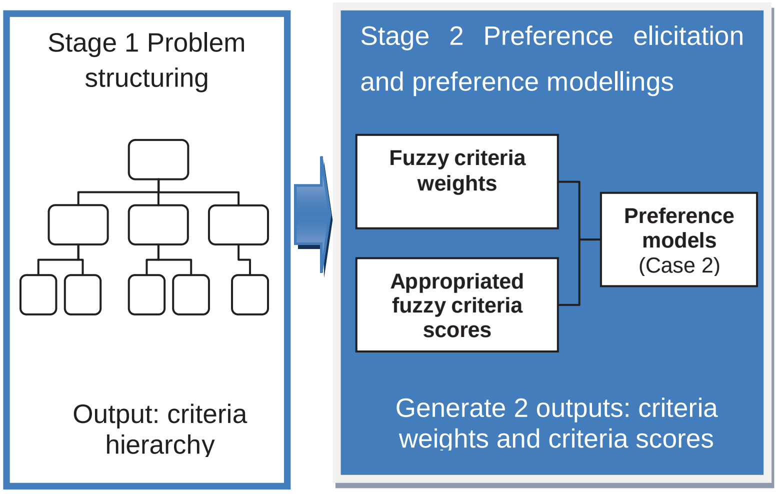


Figure 4.9 Decision support approach for case 2

Part A. Fuzzy criteria weights

Instead of expressing criteria weights by numerical crisp values, fuzzy numbers were used instead to account for judgement uncertainty associated with the mitigation value trade-offs. Recall from Section 4.2.10(0) p.128 that the mitigation value trade-offs were divided into five levels ($0m, $25m, $50m, $75m and $100m) as a guideline for DMs to judge their preferred mitigation value. Five fuzzy numbers representing these five mitigation levels (or criteria weights) were also devised — called fuzzy criteria weights. To define these five fuzzy criteria weights, the following terms need to be first introduced.

- *Linguistic variable* and *linguistic value* - a *linguistic variable* is a variable that contains a set of *linguistic values* that are not numbers but words or sentences instead of numerical values. Each linguistic value can be described by a fuzzy number which can be TFN with four real numbers [0, d_1, d_2, d_3] or TrFN [d_1, d_2, d_3, d_4]. In this study, criteria weight is a linguistic variable and the associated linguistic values are labelled as *Not Important at all* (NI), *Unimportant* (UI), *Moderate Importance* (MI), *Important* (I), and *Very Important* (VI). The linguistic values are denoted by $(\tilde{a}_s)$ where *s* is index for the label (1 = NI, 2 = UI, 3 = MI, 4 = I, 5 = VI).

$$\tilde{a}_s = (\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4, \tilde{a}_5)$$

- *Degree of membership* - the notion of a fuzzy set is a set $\tilde{A}$ of the universe of X that is characterised by the *degree of membership* $\mu_{\tilde{A}}(x)$, indicated by values in the range [0, 1], with 0.0 representing no membership and 1.0 representing absolute membership.

The fuzzy numbers for the linguistic values were chosen to roughly cover the same mitigation value trade-off ranges (express on unit scale in Table 4.14) as defined for the crisp value functions in Table 4.9. The fuzzy numbers are defined by their short notation in Table 4.14 and the formal notation in Eqn 4-10 to Eqn 4-14. A graphical presentation of the linguistic values is shown in Figure 4.10. Sensitivity analyses were carried out in Chapter 5 to test the influence of the fuzzy number definitions on the analysed decision outcomes.

Table 4.14 Linguistic values and their associated fuzzy numbers

Linguistic values	$\tilde{a}_s$	Fuzzy number for the associated linguistic values[14]	Ranges of mitigation value trade-offs (m/100)
Not important at all (NI)	$\tilde{a}_1$	(0, 0, 0.17, 0.33)	0–0.24
Unimportant (UI)	$\tilde{a}_2$	(0, 0.17, 0.33, 0.5)	0.25–0.41
Moderately important (MI)	$\tilde{a}_3$	(0, 0.33, 0.5, 0.67)	0.42–0.59
Important (I)	$\tilde{a}_4$	(0, 0.5, 0.67, 0.83)	0.60–0.75
Very important (VI)	$\tilde{a}_5$	(0.67, 0.83, 1, 1)	0.76–1

The following equations describe the fuzzy numbers by $\mu_{\tilde{a}_s}(w)$ which is the membership degree expressing the degree of belongingness to the linguistic value *s*:

$$\mu_{\tilde{a}_1}(w) = \begin{cases} 1, & w \le 0.17 \\ \dfrac{0.33 - w}{0.33 - 0.17}, & 0.17 < w \le 0.33 \\ 0, & w > 0.33. \end{cases} \tag{4-10}$$

$$\mu_{\tilde{a}_2}(w) = \begin{cases} 0, & w \le 0.17 \\ \dfrac{w - 0.17}{0.33 - 0.17}, & 0.17 < w \le 0.33 \\ \dfrac{0.5 - w}{0.5 - 0.33}, & 0.33 < w \le 0.5 \\ 0, & w > 0.5. \end{cases} \tag{4-11}$$

$$\mu_{\tilde{a}_3}(w) = \begin{cases} 0, & w \le 0.33 \\ \dfrac{w - 0.33}{0.5 - 0.33}, & 0.33 < w \le 0.5 \\ \dfrac{0.67 - w}{0.67 - 0.5}, & 0.5 < w \le 0.67 \\ 0, & w > 0.67. \end{cases} \tag{4-12}$$

$$\mu_{\tilde{a}_4}(w) = \begin{cases} 0, & w \le 0.5 \\ \dfrac{w - 0.5}{0.67 - 0.5}, & 0.5 < w \le 0.67 \\ \dfrac{0.83 - w}{0.83 - 0.67}, & 0.67 < w \le 0.83 \\ 0, & w > 0.83. \end{cases} \tag{4-13}$$

$$\mu_{\tilde{a}_5}(w) = \begin{cases} 0, & 0.67 \le w \\ \dfrac{w - 0.67}{0.83 - 0.67}, & 0.67 < w \le 0.83 \\ 1, & w > 0.83. \end{cases} \tag{4-14}$$

[14] Refer to Chapter 2 Section 2.8 for details on the definition of a fuzzy number.

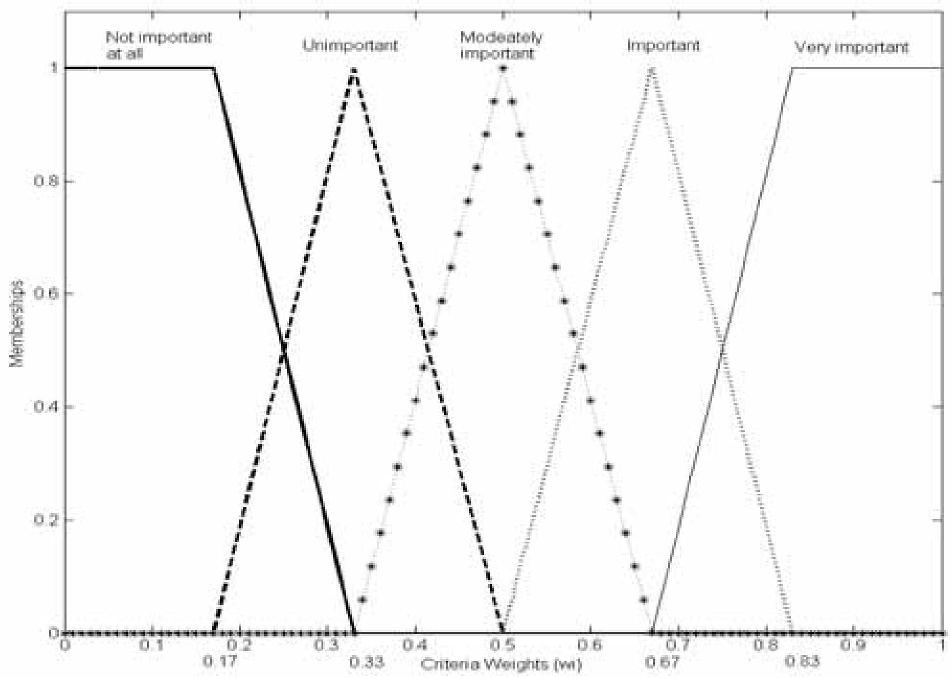


Figure 4.10 Fuzzy criteria weights $(\tilde{a}_s)$

The following describes the procedure to obtain fuzzy criteria weights. This procedure is a modification of Bonissone's (1979) FSAW method (see Appendix D1.2). Chen and Hwang (1992) and Ribeiro (1996) gave a comprehensive review of FSAW methods. The approach by Bonissone (1979) was recommended by Chen and Hwang (1992) as the practical method to use when fuzzy sets are represented by trapezoidal or triangular numbers.

Step 1. Determine which linguistic values apply $(\tilde{a}_s)$

Based on the raw crisp criteria weights (*w*) obtained from the previous case (Section 4.3.10 p.151), identify which linguistic values and the associated fuzzy numbers $(\tilde{a}_s)$ correspond to the raw crisp criteria weights or mitigation value trade-off using Table 4.14 (column 4) or Figure 4.10. The term '*activated*' is used to imply the fuzzy numbers that correspond values (crisp criteria weights or mitigation value trade-off). Two fuzzy numbers can be activated by one single raw criteria score. This is because only two fuzzy numbers are defined to overlap with each other at any one single point on the universe *x*. See Figure 4.12 for illustration.

Step 2. Obtain the appropriated fuzzy numbers $(\tilde{\boldsymbol{a}}_{\boldsymbol{as}})$

Determine the membership degrees $\mu_{\tilde{a}_s}(w)$ activated by the raw crisp criteria weights according to the membership functions of the corresponding fuzzy numbers. Substitute the raw crisp criteria weights into Eqn 4-10 to 4-14 to determine the membership degrees $\mu_{\tilde{a}_s}(w)$. The activated fuzzy numbers are appropriated by multiplying the activated membership degrees $\mu_{\tilde{a}_s}(w)$ to the fuzzy numbers to obtain the appropriated fuzzy number $(\tilde{a}_{as})$. By multiplying the fuzzy numbers by the activated membership degree $\mu_{\tilde{a}_s}(w)$, the fuzzy numbers are reduced appropriately to represent the uncertainty involved with the raw criteria score value:

$$\tilde{a}_{as} = \left(\mu_{\tilde{a}_s}(w_i) \cdot \tilde{a}_s\right) \qquad \textbf{4-15}$$

Since two fuzzy numbers can be activated at the most by one crisp criteria score value, the union between two appropriated fuzzy numbers is taken to represent the fuzzy criteria score $\tilde{a}$:

$$\tilde{a} = \tilde{a}_{as1} \cup \tilde{a}_{as_2} \qquad \textbf{4-16}$$

Part B. Fuzzy MnF and normalised criteria scores

Similar to case 1, there were five MnF but the MnF are defined as fuzzy numbers and not crisp values in case 2. The five fuzzy MnF (b_t, $t = 1, 2, 3, 4, 5$) are shown in Figure 4.11 where t is the index for the five mitigation type. Each fuzzy MnF has five linguistic values (b_{tr}) where r is the index for the linguistic values (r = 1, 2, 3, 4, 5): b_{t1} = *Very Low* (VL), b_{t2} = *Low* (L), b_{t3} = *Medium* (M), b_{t4} = *High* (H), b_t = *Very High* (VH).

Note that the raw criteria scores (x^*) were previously defined on the interval (0, 100) but in order to obtain the normalised criteria scores on the interval (0, 1) the fuzzy numbers are defined on the interval (0, 1). The reason is that the normalised criteria score can then be mapped to the unit interval. The fuzzy numbers for the five value functions are defined in Table 4.15. Each of these fuzzy numbers is conveniently denoted by the term shown in Table 4.16. For example, VL1 (very low in MnF1) represents the fuzzy number b_{11} and the definition of it is (0, 0, 0, 0.12).

Table 4.15 Fuzzy numbers (b_{tr}) for the fuzzy MnF

MnF	Very Low (VL) b_{t1}	Low (L) b_{t2}	Medium (M) b_{t3}	High (H) b_{t4}	Very High (VH) b_{t5}
1	$\tilde{b}_{11} = (0,0,0,0.12)$	$\tilde{b}_{12} = (0,0,0.12,0.31)$	$\tilde{b}_{13} = (0,12,0.31,0.58)$	$\tilde{b}_{14} = (0,0.31,0.58,1)$	$\tilde{b}_{15} = (0,0.58,1,1)$
2	$\tilde{b}_{21} = (0,0,0,0.17)$	$\tilde{b}_{22} = (0,0,0.17,0.29)$	$\tilde{b}_{23} = (0,0.17,0.39,0.66)$	$\tilde{b}_{24} = (0,0.39,0.66,1)$	$\tilde{b}_{25} = (0,0.66,1,1)$
3	$\tilde{b}_{31} = (0,0,0,0.25)$	$\tilde{b}_{32} = (0,0,0.25,0.50)$	$\tilde{b}_{33} = (0,0.25,0.50,0.75)$	$\tilde{b}_{34} = (0,0.50,0.75,1)$	$\tilde{b}_{35} = (0,0.75,1,1)$
4	$\tilde{b}_{41} = (0,0,0,0.34)$	$\tilde{b}_{42} = (0,0,0.34,0.61)$	$\tilde{b}_{12} = (0,0.34,0.61,0.83)$	$\tilde{b}_{44} = (0,0.61,0.83,1)$	$\tilde{b}_{45} = (0,0.83,1,1)$
5	$\tilde{b}_{51} = (0,0,0,0.42)$	$\tilde{b}_{52} = (0,0,0.42,0.70)$	$\tilde{b}_{12} = (0,0.42,0.70,0.88)$	$\tilde{b}_{54} = (0,0.70,0.88,1)$	$\tilde{b}_{55} = (0,0.88,1,1)$

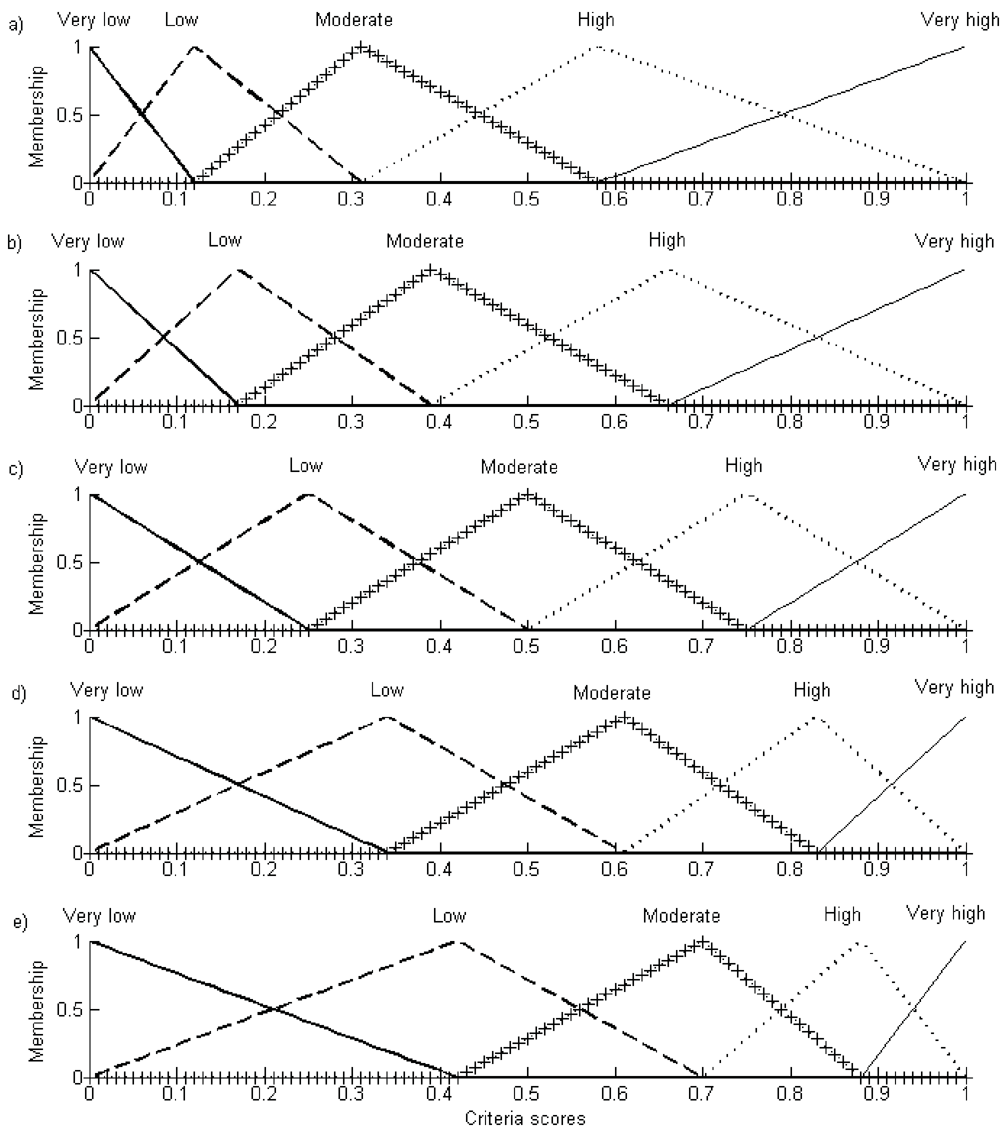


Figure 4.11 Fuzzy mitigated normalising functions: a) MnF1 b) MnF2 c) MnF3 d) MnF4 e) MnF5

Table 4.16 Simple notation for the fuzzy numbers in the fuzzy MnF

	Very Low (VL) b_{t1}	Low (L) b_{t2}	Medium (M) b_{t3}	High (H) b_{t4}	Very High (VH) b_{t5}
MnF1: t = 1	VL1	L1	M1	H1	VH1
MnF2: t = 2	VL2	L2	M2	H2	VH2
MnF3: t = 3	VL3	L3	M3	H3	VH3
MnF4: t = 4	VL4	L4	M4	H4	VH4
MnF5: t = 5	VL5	L5	M5	H5	VH5

MnF1 and MnF2 were used as preference models for criteria with lower importance (i.e. lower mitigation value trade-off). This implies that a less stringent performance scoring scheme was applied to MnF1 and MnF2 (i.e. wider support for the high and very high fuzzy numbers). Conversely, criteria with moderate to higher importance such as MnF3, MnF4 and MnF5 (i.e. higher mitigation value trade-off) had a more stringent scoring scheme (i.e. smaller support for the high and very high fuzzy numbers). The fuzzy numbers associated with the respective linguistic values for each fuzzy function are presented in Table 4.16. These fuzzy numbers were chosen to represent the logic discussed above. A sensitivity analysis was performed to evaluate the sensitivity of the final aggregated outcomes to the definition of these fuzzy numbers in Section 5.5.

The following describes the procedure to obtain fuzzy criteria scores from fuzzy MnF, which continues from the procedure described in Part A.

Step 3. Determine which linguistic values are activated $(\tilde{\boldsymbol{b}}_{tr})$

First identify which MnF applies to the criteria based on the mitigation value trade-off as discussed in Section 4.2.30 p.145. The fuzzy MnF illustrated in Figure 4.11 replaces the use of crisp MnF. Based on the selected MnF and the raw criteria score (x^*) of interest, the fuzzy numbers $(\tilde{b}_{tr})$ activated by the raw crisp criteria scores are identified. To determine which linguistic values are activated, check which specified linguistic value range(s) the raw criteria scores fall into (Figure 4.11 or Table 4.15). The membership functions of the linguistic values that occur at the raw criteria score (x^*) are activated.

Step 4. Obtain the appropriated fuzzy criteria score $(\tilde{\boldsymbol{b}}_{atr})$

Determine the membership degrees $\mu_{\tilde{b}_{tr}}(x)$ activated by the raw crisp criteria scores according to the membership functions of the corresponding fuzzy numbers. The activated fuzzy numbers are appropriated by multiplying the intrigued membership degrees $\mu_{\tilde{b}_{tr}}(x)$ to the fuzzy numbers. By appropriating the fuzzy numbers by the activated membership degree $\mu_{\tilde{b}_{tr}}(x)$, the fuzzy numbers are reduced appropriately to represent the uncertainty involved with the raw criteria score value.

$$\tilde{b}_{atr} = \left(\mu_{\tilde{b}_{tr}}(x_i) \cdot \tilde{b}_{tr}\right) \quad \text{4-17}$$

Since two fuzzy numbers can be activated at most by one crisp criteria score, the union between two appropriated fuzzy numbers is taken to represent the fuzzy criteria score.

$$\tilde{b} = \tilde{b}_{atr_1} \cup \tilde{b}_{atr_2} \quad \text{4-18}$$

Case 2. Example

Consider the same example from Case 1 Section 4.3.10 p.151. Here, the criteria weights and criteria scores for the four technical criteria (security of supply, reliability, flexibility and risks) were described as fuzzy numbers. The following describes the process to obtain fuzzy criteria weights and fuzzy criteria scores.

Part A. Fuzzy criteria weights

Step 1. Determine which linguistic values apply ($\tilde{\boldsymbol{a}}_s$)

The mitigation value trade-offs and the associated MnF types determined in the previous example are presented here again in Table 4.17. The same MnF types apply in this case but instead of using the crisp MnF, fuzzy MnF were used instead. Linguistic values and corresponding fuzzy numbers for the four criteria are shown in Table 4.17.

Table 4.17 Activated fuzzy criteria weights ($\tilde{\boldsymbol{a}}_s$)

Technical criteria	Mitigation value trade-offs (m_i)	Crisp criteria weights (w_i)	MnF types	Activated fuzzy criteria weights[15]	Fuzzy criteria weights
Security of supply (c_6)	50	0.5	MnF3	MI	(0, 0.33, 0.5, 0.67)
Reliability (c_7)	50	0.5	MnF3	MI	(0, 0.33, 0.5, 0.67)
Flexibility (c_8)	0	0	MnF1	NI	(0, 0, 0.17, 0.33)
Risk (c_9)	0	0	MnF1	NI	(0, 0, 0.17, 0.33)

MI = moderately important; NI = not important at all

The fuzzy criteria weights for security of supply (c_6) and reliability (c_7) were both *moderate important (MI)* (m_6 = m_7 = 50). Similarly, the fuzzy criteria weights for flexibility (c_8) and risk (c_9) were both *not important at all (NI)*. Note that in this particular example, only one fuzzy criteria weight was activated for each criterion. The

[15] The linguistic values and the corresponding fuzzy numbers for the fuzzy criteria weights were determined using Figure 4.11.

following figure shows the fuzzy number (*not important at all, NI*) ($\tilde{a}_1$) activated by the $m = 0$ or $w = 0$ assigned to the criterion flexibility by the expert M2 (Figure 4.12).

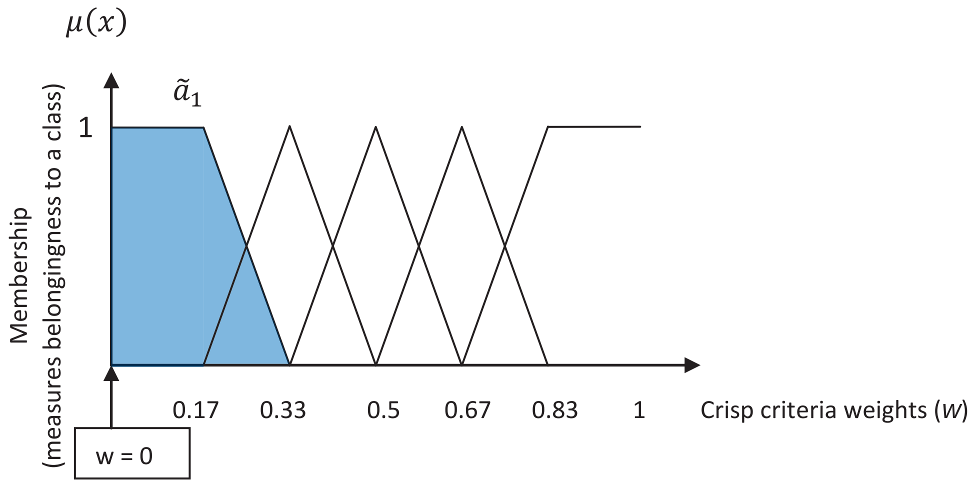


Figure 4.12 Fuzzy criteria weight activated by w_8 = 0 evaluated by water manager M2 for Strategy A

Step 2. Appropriated fuzzy criteria weights ($\tilde{a}_{as}$)

The activated membership for the fuzzy criteria weight *NI* at ($w = 0$) was obtained using the corresponding fuzzy membership functions (Eqn 4-10) as follows:

$$\mu_{\tilde{a}_1}(w) = \begin{cases} 1, & w \leq 0.17 \\ \frac{0.33 - w}{0.33 - 0.17}, & 0.17 < w \leq 0.33 \\ 0, & w > 0.33. \end{cases}$$

$$\mu_{\tilde{a}_1}(0) = 1$$

Note that in this example, only one fuzzy number was activated for each criterion (Table 4.18). If there were two fuzzy numbers activated, then there would be two membership degrees for each fuzzy number.

Table 4.18 Activated membership $\mu_{\tilde{a}}(x_i)$ for the corresponding fuzzy criteria weights $(\tilde{a}_s)$

Technical criteria	Mitigation value trade-offs (m_i)	Crisp criteria weights (w_i)	MnF Types	Activated fuzzy criteria weights $(\tilde{a}_s)$	Activated membership degree $\mu_{\tilde{a}}(x_i)$
Security of supply (c_6)	50	0.5	MnF3	Moderate important (MI)	1.00
Reliability (c_7)	50	0.5	MnF3	Moderate important (MI)	1.00
Flexibility (c_8)	0	0	MnF1	Not important at all (NI)	1.00
Risk (c_9)	0	0	MnF1	Not important at all (NI)	1.00

The activated fuzzy number NI ($\tilde{a}_1$) was multiplied by the activated membership which is $\mu_{\tilde{a}_1}(0) = 1$ in this case to obtain the appropriated fuzzy criteria weight ($\tilde{a}_{as}$). Since the activated membership value was 1, the appropriated fuzzy criteria weight was the same as the raw fuzzy criteria weight ($\tilde{a}_1$) (Figure 4.13):

$$\tilde{a}_{a1} = (1 \cdot \tilde{a}_1)$$

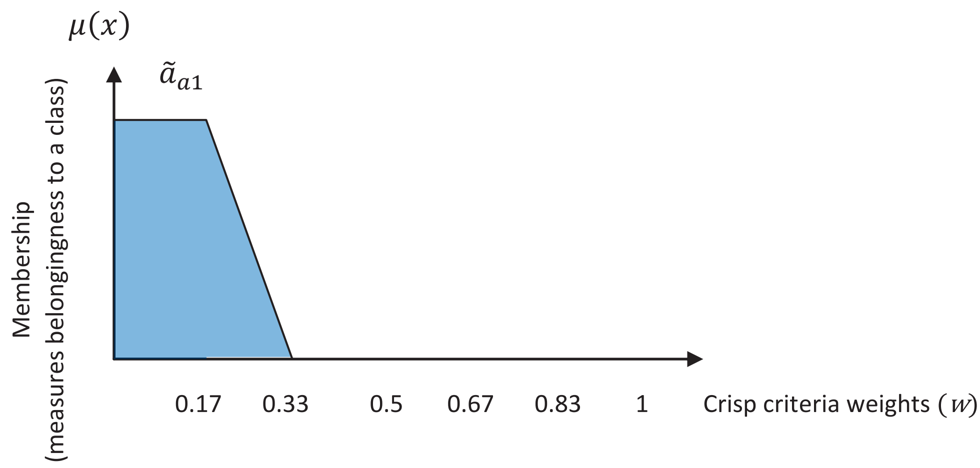


Figure 4.13 Appropriated fuzzy criteria weight $(\tilde{a}_{as})$

Part B. Fuzzy MnF and fuzzy criteria scores

<u>Step 3. Determine which linguistic values are activated</u> $(\tilde{b}_{tr})$

Consider the criterion risks, the raw criteria score for strategy A is x^* = 0.56 (Table 4.5). The mitigation value trade-off given by the water manager M2 was m_9 = 0, hence MnF1 applied in this case (Table 4.12). The following figure shows MnF1 (see Figure 4.11) and the two linguistic values H1 and VH1 are activated by the raw criteria score (x = 0.56) represented by $(\tilde{b}_{13})$ and $(\tilde{b}_{14})$ respectively (Figure 4.14). These two linguistic values are activated because at $x^* = 0.56$, the membership functions of the corresponding fuzzy numbers $(\tilde{b}_{13})$ and $(\tilde{b}_{14})$ occurred.

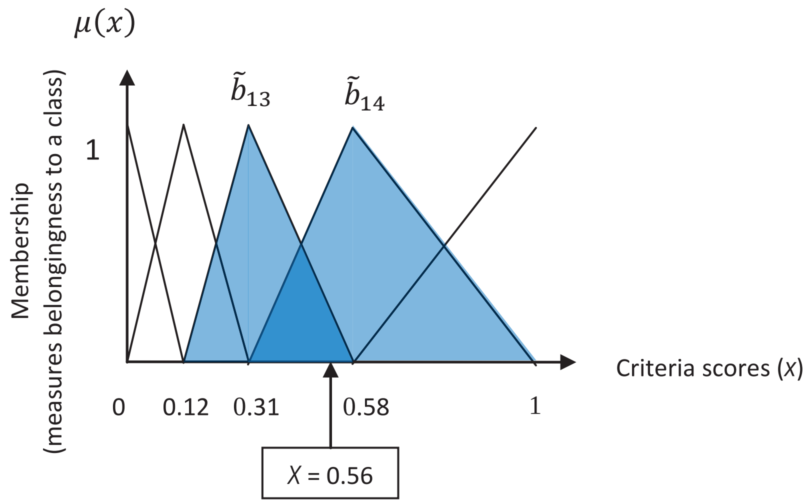


Figure 4.14 Two activated linguistic values $(\tilde{b}_{13})$ and $(\tilde{b}_{14})$ in fuzzy MnF1 for criterion risks

The raw criteria scores for the technical criteria and the determined value functions types are presented in Table 4.19. The raw criteria scores are extracted from Table 4.5, but as explained in Section 4.3.20 p.157 the raw criteria scores are mapped to the unit interval for standardisation. The activated fuzzy numbers for all of the raw criteria scores based on water manger M2's evaluation are presented in Table 4.20. The corresponding activated membership degrees $\left(\mu_{\tilde{b}_{tr}}(x)\right)$ are presented in Table 4.21.

Table 4.19 Raw technical criteria scores and MnF types assigned by water manger M2

Technical criteria	Raw criteria scores ($x_i^*/100$)					MnF
Strategies	**A**	**B**	**C**	**D**	**E**	**-**
Security of supply (c_6)	0.38	0.34	0.34	0.50	0.56	MnF3
Reliability (c_7)	0.58	0.76	0.64	0.62	0.72	MnF3
Flexibility (c_8)	0.63	0.53	0.63	0.60	0.67	MnF1
Risk (c_9)	0.56	0.69	0.70	0.63	0.52	MnF1

Table 4.20 Activated fuzzy numbers $(\tilde{b}_{tr})$ for the raw criteria scores

Criteria	First activated fuzzy number					Second activated fuzzy number				
Strategies	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Security of supply (c_6)	L3	L3	L3	M3	M3	M3	M3	M3	-	H3
Reliability (c_7)	M3	H3	M3	M3	M3	H3	VH3	H3	H3	H3
Flexibility (c_8)	H1	M1	H1	H1	H1	VH1	H1	VH1	VH1	VH1
Risk (c_9)	M1	H1	H1	H1	M1	H1	VH1	VH1	VH1	H1

Table 4.21 Activated membership $\left(\mu_{\tilde{b}_{tr}}(x)\right)$ for the corresponding fuzzy criteria scores

Criteria	First activated fuzzy number					Second activated fuzzy number				
Strategies	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
Security of supply (c_6)	0.48	0.64	0.64	1.00	0.76	0.52	0.36	0.36	0.00	0.24
Reliability (c_7)	0.68	0.96	0.44	0.52	0.12	0.32	0.04	0.56	0.48	0.88
Flexibility (c_8)	0.88	0.19	0.88	0.95	0.79	0.12	0.81	0.12	0.05	0.21
Risk (c_9)	0.07	0.74	0.71	0.88	0.22	0.93	0.26	0.29	0.12	0.78

<u>Step 4. Obtain the appropriated fuzzy criteria score</u> $(\tilde{b}_{atr})$

The activated membership $\left(\mu_{\tilde{b}_{tr}}(x)\right)$ for the two fuzzy numbers $(\tilde{b}_{13})$ and $(\tilde{b}_{14})$) at (x = 0.56) (see Table 4.21) were obtained using the corresponding fuzzy membership functions as follows:

$$\mu_{\tilde{b}_{13}}(x) = \begin{cases} \dfrac{x-0.12}{0.31-0.12}, & 0.12 < x \leq 0.31 \\ \dfrac{0.58-x}{0.58-0.31}, & 0.31 < x \leq 0.58 \end{cases} \quad \textbf{4-19}$$

$$\mu_{\tilde{b}_{14}}(x) = \begin{cases} \dfrac{x-0.31}{0.58-0.31}, & 0.31 < x \leq 0.58 \\ \dfrac{1-x}{1-0.58}, & 0.58 < x \leq 1 \end{cases} \quad \textbf{4-20}$$

$$\mu_{\tilde{b}_{13}}(0.56) = \frac{0.58-0.56}{0.58-0.31} = 0.07$$

$$\mu_{\tilde{b}_{14}}(0.56) = \frac{0.56-0.31}{0.58-0.31} = 0.93$$

The two fuzzy numbers $(\tilde{b}_{13})$ and $(\tilde{b}_{14})$ were multiplied by the corresponding activated membership degrees:

$$\tilde{b}_{a13} = 0.07 \cdot \tilde{b}_{13}$$

$$\tilde{b}_{a14} = 0.93 \cdot \tilde{b}_{14}$$

The appropriated fuzzy numbers $\tilde{b}_{a13}$ and $\tilde{b}_{a14}$ are coloured as shown in the following figure. Point A and point B as shown in Figure 4.15 are the activated memberships $\mu_{\tilde{b}_{13}}(0.07)$ and $\mu_{\tilde{b}_{14}}(0.93)$ respectively. The union of the two shaded areas is the fuzzy crisp criteria score for criterion flexibility at $x^* = 0.56$ $(\tilde{b}_{risks})$ (Figure 4.16).

$$\tilde{b}_{risks} = \tilde{b}_{a13} \cup \tilde{b}_{a14}$$

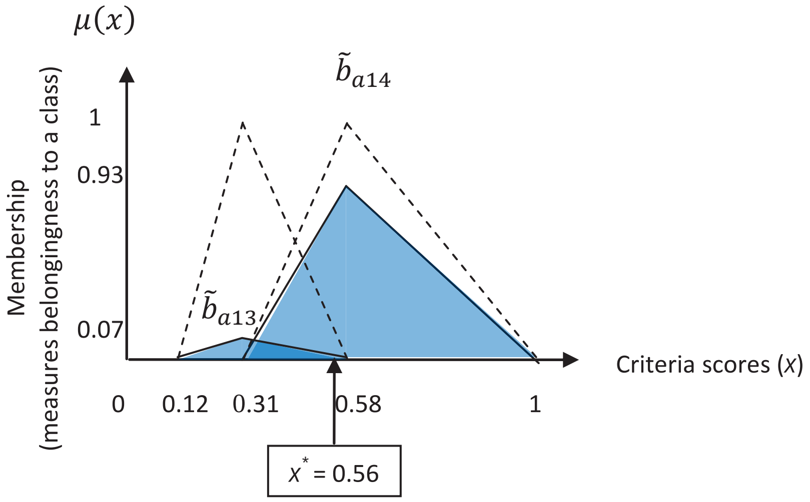


Figure 4.15 Appropriated fuzzy criteria scores $(\tilde{b}_{a14})$ and $(\tilde{b}_{a15})$ at x = 0.56

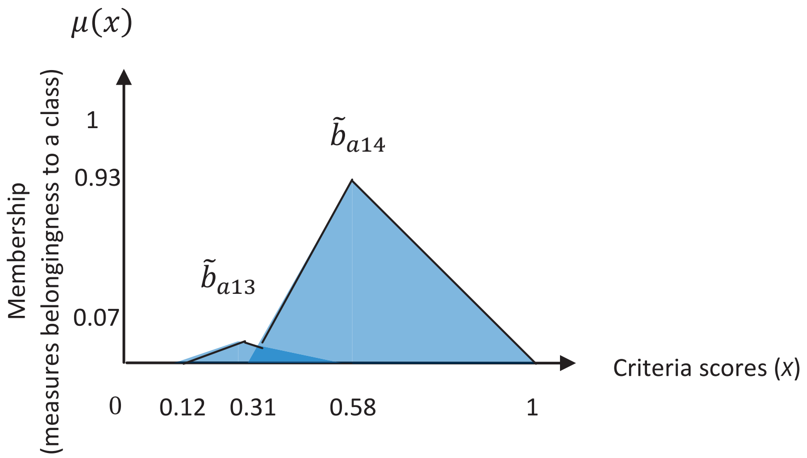


Figure 4.16 Fuzzy criteria score for risks $(\tilde{b}_{risks})$

4.3.3 Case 3. With criteria interaction

In this case, the following assumptions were made:

- criteria were not assumed to be preferentially independent and thus the family of averaging aggregations[16] could not be applied. The Choquet integral was used instead as an aggregation tool to account for criteria interaction. (The problem of criteria interaction was explained in Section 2.5.4 p.54 and details about the Choquet integral are provided in Appendix D2).
- judgement uncertainty was not considered and therefore crisp criteria scores and normalised crisp criteria scores were determined.

This section explains how criteria interaction was considered in the preference modelling stage. Two outputs from this case were (Figure 4.17):

- Shapley and interaction index (criteria weights)
- normalised crisp criteria scores.

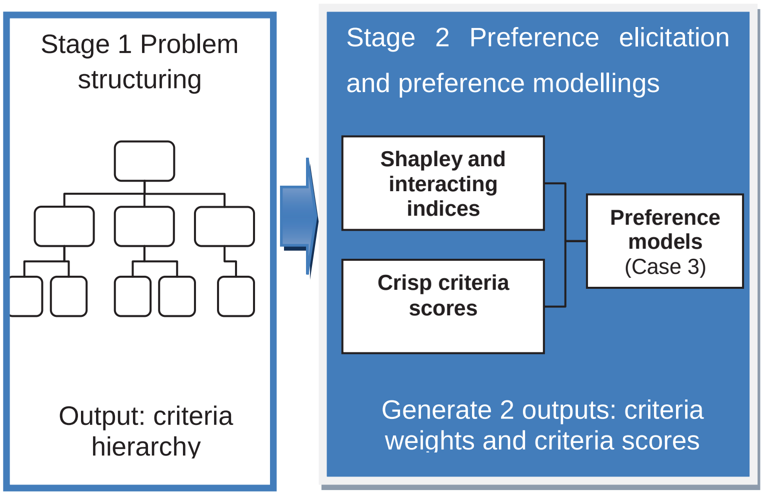


Figure 4.17 Decision support approach for Case 3

[16] Averaging operators treat criteria as preferentially independent.

Part A. Shapley index and interaction index

This section presents the procedure to determine Shapley index and interaction index (see Appendices D2.2, D2.3). Recall that the 2-additive Choquet integral is defined as follows:

$$q = \sum_{i=1}^{n} \phi_i x_i - \frac{1}{2}\sum_{i=1}^{n} I_{ij}\left|x_i - x_j\right| \quad \textbf{4-21}$$

Where:

q is the aggregated score using the 2-additive Choquet integral

ϕ_i is the Shapley index for criterion *i*

x_i and x_j are the criteria scores for criterion *i* and *j*

I_{ij} is the interaction index between criterion *I* and *j*.

To apply 2-additive Choquet integrals, the following two parameters are required to be determined:

- *Shapley index* – the importance of individual criterion with respect to its contribution to the overall decision problem
- *Interaction index* – measures the level of interaction between pairs of criteria.

The process to determine Shapley and interaction indices was partially based on an approach which extends Measuring attractiveness by a categorical-based evaluation technique (MACBETH) to the Choquet integral (Grabisch *et al.*, 2003; Berrah and Clivilé, 2007; Clivillé *et al.*, 2007). In the original approach, MACBETH is used to compute criteria scores by pairwise comparison using linguistic interval scales. Detailed explanation of MACBETH is provided in Appendix A1.4. In this case study, criteria scores were computed using mitigated normalising functions with the final decision outcomes aggregated by the Choquet integral. Only the linguistic interval scale from MACBETH was used to determine strength of preference between criteria. The approach followed here differed from the original approach in that the criteria scores were not derived by using MACBETH.

Two pieces of preferential information were required in order to determine Shapley and interaction indices which were tied to the procedure described following after this:

- Individual criteria preference and the strength of preference between the criteria

- Preference for pairs of criteria and the strength of preference between them.

The first piece of information was obtained using the procedure described in Step 1 and Step 2. The second piece of information was obtained using the procedure described in Step 3 and Step 4.

The following procedure was followed to determine these two pieces of preferential information.

Step 1. Rank the individual criteria

Consider an alternative S_i in which there is only one criterion (c_i) at its best performance level and all the other criteria are at their worst performance level. This fictitious situation can be denoted by a vector of elementary expressions $(p_1, \dots, p_i, \dots, p_n) = (0, \dots, 0,1,0, \dots, 0)$ where p_i characterises c_i and $p_i = 1; p_1, \dots p_{i-1}, p_{i+1}, \dots, p_n = 0$.

Given two fictive situations S_i and S_j representing two alternatives where c_i and c_j are at their best performance level respectively. These two situations can be expressed using the vectors $(0, \dots, 0, p_i = 1,0, \dots, 0)$ and $\left(0, \dots, 0, p_j = 1,0, \dots, 0\right)$. There are two possible ordering of preference: S_i is preferred to S_j or S_i is equivalent to S_j. The preference can be described as:

- The DM prefers S_i to S_j (i.e. $S_i \succ S_j \Leftrightarrow q_{(0,..,p_i=1,...,0)} \succ q_{(0,..,p_j=1,...,0)}$)
- The DM's preference between S_i and S_j is equivalent, (i.e. $S_i \approx S_j \Leftrightarrow q_{(0,..,p_i=1,...,0)} = q_{(0,..,p_j=1,...,0)}$.

These two preference relationships can be denoted simply as $q_i \succ q_j$ and $q_i = q_j$ where q is the aggregated performance score for S using the Choquet integral (Eqn 4-21).

Step 2. Determine strength of preference between individual criteria

The second step involves assessing the strength of preference between the ranked criteria. To rate the strength of preference between the ranked criteria, a set of linguistic values from MACBETH is used (*null, very weakly preferred, weakly preferred, moderately preferred, strongly preferred, very strongly preferred, extremely preferred*) (Bana e Costa *et al.*, 2005). The linguistic variables are associated with a numerical value $h \in [0,6]$ with null being 0 and extreme being 6 (Figure 4.18). DMs can determine the strength of preferences between criteria c_i and c_j under the form:

q_i is *null/very weakly/weakly/moderately/strongly/very strongly/extremely* preferred to q_j

The expression of the strength of preference between two criteria $q_i \succ q_j$ can be written in the following preference equation form:

$$q_i - q_j = h\alpha \quad \textbf{4-22}$$

where α is a coefficient necessary to meet the condition, q_i and $q_j \in [0,1]$ and h is the numerical scores associated with the MACBETH linguistic values.

For q_i, there is only one criterion c_i at its best performance level, therefore $x_i = 1$ and $x_j = 0$ (x_j refers to all other criteria in the set). Similarly, for q_j, c_j is the only criterion at its best, therefore $x_i = 0$ and $x_j = 1$ (x_i refers to all other criteria in the set). Substituting the x_i and x_j values into Eqn 4-21, the expressions for q_i and q_j are defined by Eqn 4-23 and Eqn 4-24 respectively as follows:

$$q_i = \phi_i - \frac{1}{2}\sum_{j=1}^{n} I_{ij} \quad \textbf{4-23}$$

where $x_i = 1$ and $x_j = 0$ and

$$q_j = \phi_j - \frac{1}{2}\sum_{i=1}^{n} I_{ij} \quad \textbf{4-24}$$

where $x_i = 0$ and $x_j = 1$.

Substituting Eqn 4-23 and Eqn 4-24 into Eqn 4-22, the following equation is obtained.

$$\left(\phi_i - \frac{1}{2}\sum_{j=1}^{n} I_{ij}\right) - \left(\phi_j - \frac{1}{2}\sum_{i=1}^{n} I_{ij}\right) = h\alpha \quad \textbf{4-25}$$

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred
h = 0	h = 1	h = 2	h = 3	h = 4	h = 5	h = 6

Figure 4.18 Linguistic values for preference scale and associated *h* value

Step 3. Rank pairs of criteria

Pairwise comparison is conducted to model interaction between criteria. For *n* criteria, there are *(n-1)!* pairs of criteria to compare with each other. To rank the importance between pairs of criteria (c_{ij}), a similar procedure to the one described in Step 1 is used. For a fictive alternative S_{ij} where two criteria c_i and c_j are at their best performance levels and all the other criteria are at their worst performance levels, the elementary expression vector is denoted as $(0, \dots, 0, p_i = 1, \dots, p_j = 1, \dots, 0)$. Consider two fictive alternatives S_{ij} and S_{ab} There are two possible ordering of preference: S_{ij} is preferred to S_{ab} or S_{ij} is equivalent to S_{ab}. The preference can be described as:

- The DM prefers S_{ij} to S_{ab}

  (i.e. $S_{ij} \succ S_{ab} \Leftrightarrow q_{(0,..,p_i=1,\dots,p_j=1,\dots,0)} \succ q_{(0,..,p_a=1,\dots,p_b=1,\dots,0)}$)
- The DM's preference between S_{ij} and S_{ab} is equivalent,

  (i.e. $S_{ij} \approx S_{ab} \Leftrightarrow q_{(0,..,p_i=1,\dots,p_j=1,\dots,0)} = q_{(0,..,p_a=1,\dots,p_b=1\dots,0)}$.

These two preference relationships can be denoted simply as $q_{ij} \succ q_{ab}$ and $q_{ij} = q_{ab}$ where q is the aggregated performance score for S using the Choquet integral (Eqn 4-21).

To rank between S_{ij} and S_{ab}, this questioning technique can be utilised, "*What is the effect on the overall aggregated performance if two criteria are simultaneously at their best performance level but other criteria are at their worst performance level?*".

Step 4. Determine strength of preference between pairs of criteria

Determine the strength of preference between the pairs of criteria using the same linguistic values from Figure 4.18. The expression of the strength of preference between pairs of criteria can be written in the modified form of Eqn 4-22. To express q for S_{ij}, consider a set of indices k that does not contain i and j $(k \in C\backslash ij,)$ where C is the set of criteria indices and $C\backslash ij$ is the set of criteria indices that does not contain i and j. The two elementary expressions p_i and p_j are at their best performance levels $(p_i = p_j = 1)$, and all the other elementary expressions are at their worst performance level $(p_k = 0)$. Given that c_i and c_j are at their best performance levels, $(x_i = x_j = 1)$ and c_k is at the worst performance level $(x_k = 0)$, q_{ij} can be expressed by Eqn 4-26 using Eqn 4-21.

$$q_{ij} = \phi_i + \phi_j - \frac{1}{2}\sum_{k=1}^{n}\left(I_{ik} + I_{jk}\right) \quad \textbf{4-26}$$

Eqn 4-26 can be substituted in Eqn 4-22 to obtain Eqn 4-27.

$$\left(\phi_i + \phi_j - \frac{1}{2}\sum_{k=1}^{n}\left(I_{ik} + I_{jk}\right)\right) - \left(\phi_a + \phi_b - \frac{1}{2}\sum_{k=1}^{n}\left(I_{ak} + I_{bk}\right)\right) = h\alpha \quad \textbf{4-27}$$

Step 5. Determine Shapley and interaction indices

A system of equations is obtained in the form of $q_i - q_j = h\alpha$ by considering the criteria as individuals and as pairs. Together with the condition $\sum_{i=1}^{n} \phi_i = 1$, the system of equations is expressed as a matrix and solved for ϕ and I.

Part B. Crisp MnF and normalised criteria scores

The process of determining crisp criteria normalising functions and normalised criteria scores were the same as described in Section 4.3.10 p.149.

Case 3. Example

Part A. Shapley index and Interaction index

The following illustrates the process of determining Shapley and interaction indices using the same example from Section 4.3.10 p.151. Four fictive situations were devised for the four technical criteria: $S_{\text{security of supply}}$, $S_{\text{reliability}}$, $S_{\text{flexibility}}$ and S_{risks} or more simply denoted as (S_1, S_2, S_3, S_4)[17]. For example, the fictive situation $S_{\text{security of supply}}$ (S_1) implied that only the criterion security of supply was at its best performance level and all the other criteria (reliability, flexibility and risks) were at their worst performance levels. These four fictive situations were associated with the corresponding aggregated scores by the Choquet integrals (q_1, q_2, q_3, q_4).

In this example with four criteria (n = 4), there were four Shapley and six interaction indices (i.e. (4-1)! = 6) to be determined. Therefore ten preference equations were required to determine the ten indices. An additional fictive situation on the referendum case S_0 where $q_{(0,0,0,0)}$ or q_0 (i.e. all criteria are at their worst performance levels) was introduced to obtain two out of the ten required preference equations.

[17] For simplicity, the indices for these four fictive situations were denoted as 1 to 4 instead of the original indices c_6, c_7, c_8, c_9 given for the four technical criteria.

Step 1. Rank the individual criteria

The four criteria were ranked by considering the four fictive situations (S_1, S_2, S_3, S_4) as shown in Table 4.22.

Table 4.22 Example Case 3. Step 1

	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5
Criteria	**Flexibility** (S_3)	is preferred to	**Risks** (S_4)	is preferred to	**Security of Supply** (S_1)	is preferred to	**Reliability** (S_2)	is preferred to	**Referendum** (S_0)
Choquet integral	q_3	$\succ$	q_4	$\succ$	q_1	$\succ$	q_2	$\succ$	q_0

Step 2. Strength of preference between individual criteria

The strengths of preference between the individual criteria were expressed using MACBETH's linguistic values.

Table 4.23 Example Case 3. Step 2

	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5
Criteria	**Flexibility** (c_3)	Is weakly preferred to	**Risks** (c_4)	Is moderately preferred to	**Security of Supply** (c_1)	Is moderately preferred to	**Reliability** (c_2)	Is weakly preferred to	**Referendum**
Choquet integral	q_3	$\succ$	q_4	$\succ$	q_1	$\succ$	q_2	$\succ$	q_0
	q_3	h = 2	q_4	h = 3	q_1	h = 3	q_2	h = 2	q_0

Using Eqn 4-22, the criteria preference and strength of preference from Table 4.23 are translated into the following preferential relationships:

Flexibility was *weakly preferred* over risks:

$$q_3 - q_4 = 2\alpha \quad \textbf{4-28}$$

Risks were *moderately preferred* over security of supply:

$$q_4 - q_1 = 3\alpha \quad \textbf{4-29}$$

Security of supply was *moderately preferred* over reliability:

$$q_1 - q_2 = 3\alpha \quad \textbf{4-30}$$

Reliability was *weakly preferred* over referendum

$$q_2 - q_0 = 2\alpha \quad \textbf{4-31}$$

Eqn 4-28 is expanded into the following Eqn 4-32 using Eqn 4-25. The process of identify the interaction indices (I_{ij}) is illustrated in Figure 4.19. the following preference relationship between q_3, q_4 is obtained:

$$q_3 - q_4 = \left(\phi_3 - \frac{1}{2}(I_{13} + I_{23} + I_{34})\right) - \left(\phi_4 - \frac{1}{2}(I_{14} + I_{24} + I_{34})\right) = 2\alpha$$

$$q_3 - q_4 = \phi_3 - \phi_4 - \frac{1}{2}(I_{13} - I_{14} + I_{23} - I_{24}) = 2\alpha \quad \textbf{4-32}$$

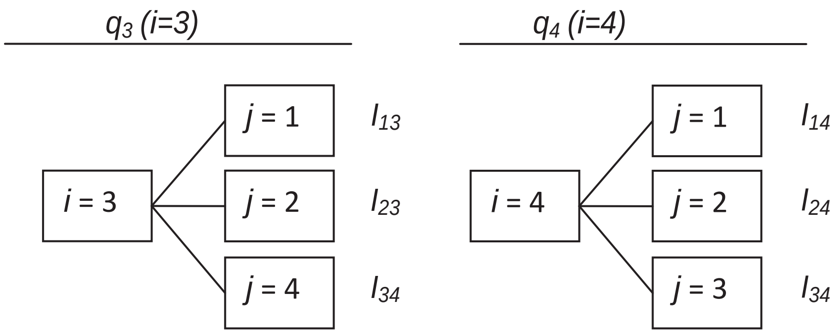


Figure 4.19 Illustration of Eqn 4-25 for the preference relation Eqn 4-32

Similarly, the preference relationship between q_4, q_1 is obtained by expanding Eqn 4-29 using Eqn 4-25:

$$p_4 - p_1 = \phi_4 - \phi_1 - \frac{1}{2}(-I_{12} - I_{13} + I_{24} + I_{34}) = 3\alpha \quad \textbf{4-33}$$

The preference relationship between q_1, q_2 is obtained using Eqn 4-30 and Eqn 4-25:

$$p_1 - p_2 = \phi_1 - \phi_2 - \frac{1}{2}(I_{13} + I_{14} - I_{23} - I_{24}) = 3\alpha \quad \textbf{4-34}$$

The preference relationship between q_1, q_2 is obtained using Eqn 4-31 and Eqn 4-25:

$$p_2 - p_0 = \phi_2 - \frac{1}{2}(I_{12} + I_{23} + I_{24}) = 2\alpha \quad \textbf{4-35}$$

Step 3. Rank pairs of criteria

Six pairs of criteria were formed for comparisons based on a combination of two criteria at their best performance levels (a score of 1) and the other two criteria at their worst performance levels (a score of 0) as shown in Table 4.26. These six pairs of criteria were represented by six fictive situations S_{12}, S_{13} S_{14}, S_{23} S_{24}, S_{34} or by six Choquet integrals for the corresponding fictive situations q_{12}, q_{13} q_{14}, q_{23} q_{24}, q_{34}. For example,

S_{12} referred to a fictive situation where security of supply (c_1) and reliability (c_2) were at their best performance levels and the other two criteria (flexibility and reliability) were at their worst performance levels. An additional case S_0 with the worst performance levels for all criteria was added to the *(n-1)!* comparison to obtain preference over the referendum case. The associated preference vectors for the six pairs of criteria and the associated vectors of elementary expressions are expressed as follows (Table 4.24):

Table 4.24 Six fictive situations or pairs of criteria for comparisons

Fictive situations (S_{ij})	Choquet integrals (q_{ij})	Vectors (p_1, p_2, p_3, p_4)	Elementary expressions
Security of supply + Reliability S_{12}	q_{12}	(1, 1, 0, 0)	where $p_1 = p_2 = 1$, $p_3 = p_4 = 0$
Security of supply +Flexibility S_{13}	q_{13}	(1, 0, 1, 0)	where $p_1 = p_3 = 1$, $p_2 = p_4 = 0$
Security of supply + Risk S_{14},	q_{14},	(1, 0, 0, 1)	where $p_1 = p_4 = 1$, $p_2 = p_3 = 0$
Reliability + Flexibility S_{23},	q_{23}	(0, 1, 1, 0)	where $p_2 = p_3 = 1$, $p_1 = p_4 = 0$
Reliability + Risks S_{24},	q_{24}	(0, 1, 0, 1)	where $p_2 = p_4 = 1$, $p_1 = p_3 = 0$
Flexibility + Risks S_{34},	q_{34}	(0, 0, 1, 1)	where $p_3 = p_4 = 1$, $p_1 = p_2 = 0$
Referendum c_0	q_{34}	(0, 0, 0, 0)	where $p_1 = p_2 = 1$, $p_3 = p_4 = 0$

The best and the worst cases for each criterion are explained in Table 4.25.

Table 4.25 Description of best and worst cases for the four technical criteria

	Criteria	Worst (p = 0)	Best (p = 1)
c_1	Security of supply	Reliance on one single source	Reliance on multiple sources (i.e. dam/recycle water)
c_2	Reliability of services	High reliance on climate sensitive water source	Low reliance on climate sensitive water sources
c_3	Flexibility	Poor operational flexibility	Fully capable of adapting to new changes
c_4	Risks	High system failure risk	Low system failure risk

Table 4.26 Seven comparisons for *n* criteria plus the referendum case

Criteria at their best	Security of supply + Reliability S_{12}	Security of supply + Flexibility S_{13}	Security of supply + Risk S_{14}	Reliability + Flexibility S_{23}	Reliability + Risks S_{24}	Flexibility + Risks S_{34}	Referen-dum S_0
Security of supply (c_1)	1	1	1	0	0	0	0
Reliability (c_2)	1	0	0	1	1	0	0
Flexibility (c_3)	0	1	0	1	0	1	0
Risk (c_4)	0	0	1	0	1	1	0

The preferences obtained from the water manager M2 are outlined in Table 4.27.

Table 4.27 Preference for the 7 fictive situations or pairs of criteria given by water manager M2 (1)

Rank	Fictive situation (S_{ij})	Choquet integral	Preferred over	Fictive situation (S_{ij})	Choquet integral
1	Flexibility + Risks (S_{34})	q_{34}	≻	Security of supply +Flexibility (S_{13})	q_{13}
2	Security of supply +Flexibility (S_{13})	q_{13}	≻	Reliability + Flexibility (S_{23})	q_{23}
3	Reliability + Flexibility (S_{23})	q_{23}	≻	Security of supply + Risk (S_{14})	q_{14}
4	Security of supply + Risk (S_{14})	q_{14}	≻	Reliability + Risks (S_{24})	q_{24}
5	Reliability + Risks (S_{24})	q_{24}	≻	Security of supply + Reliability (S_{12})	q_{12}
6	Security of supply + Reliability (S_{12})	q_{12}	≻	Referendum (S_0)	q_0

To assist the expert M2 in judging the ranking of the seven fictive situations during the interview, a set of cards with the six pairwise comparisons labelled on them were given to M2 to sort. This follows Simos' (1990) procedure, which is detailed in Appendix B2.1. The cards are illustrated in Figure 4.20.

Step 4. Strength of preference between pairs of criteria

After the first six pairs of criteria were arranged in order of preference, M2 was asked to rate the strength of preference using the linguistic preference scales again (Figure 4.18). This was done by inserting a blank card in between the cases and M2 labelled the strength of preference on the blank card. An additional seventh case with the worst performance levels for all criteria was added to the set to obtain preference for the referendum case ($q_{(0,0,0,0)}$).

Figure 4.20 Cards for assessing criteria interaction

A special note about making these comparisons is that it is potentially erroneous to not consider criteria that occurred in both fictive situations. For example, for the comparison between the two fictive situations under Rank 1 in Table 4.28: Flexibility + Risks (S34) and Security of supply + Flexibility (S13). The DM could easily be misled by comparing the importance of only security of supply and reliability since flexibility occurred in both fictive situations. This is not the correct way of making the comparisons because the idea is to encourage DMs to consider the synergistic influence when two criteria are simultaneously satisfied.

Table 4.28 Preference for the 7 fictive situations or pairs of criteria given by water manager M2 (2)

Rank	Fictive situation (S_{ij})	Choquet integral	Strength of preference (linguistic)	Strength of preference (h value)	Fictive situation (S_{ij})	Choquet integral
1	Flexibility + Risks (S_{34})	q_{34}	Strongly preferred	4	Security of supply +Flexibility (S_{13})	q_{13}
2	Security of supply +Flexibility (S_{13})	q_{13}	Moderately preferred	3	Reliability + Flexibility (S_{23})	q_{23}
3	Reliability + Flexibility (S_{23})	q_{23}	Moderately preferred	3	Security of supply + Risk (S_{14})	q_{14}
4	Security of supply + Risk (S_{14})	q_{14}	Weakly preferred	2	Reliability + Risks (S_{24})	q_{24}
5	Reliability + Risks (S_{24})	q_{24}	Moderately preferred	3	Security of supply + Reliability (S_{12})	q_{12}
6	Security of supply + Reliability (S_{12})	q_{12}	Extremely preferred	6	Referendum (S_0)	q_0

Using Eqn 4-22, the criteria preference and strength of preference from Table 4.28 are translated into the following preferential relationships:

Rank 1: Flexibility + Risks (S_{34}) was *strongly preferred* over Security of Supply + Flexibility (S_{13}):

$$q_{34} - q_{13} = 4\alpha \quad \text{4-36}$$

Rank 2: Security of Supply + Flexibility (S_{13}) were *moderately preferred* over Reliability + Flexibility (S_{23}):

$$q_{13} - q_{23} = 3\alpha \quad \text{4-37}$$

Rank 3: Reliability + Flexibility (S_{23}) was *moderately preferred* over Security of supply + Risk (S_{14}):

$$q_{23} - q_{14} = 3\alpha \quad \text{4-38}$$

Rank 4: Security of supply + Risk (S_{14}) was *weakly preferred* over Reliability + Risks (S_{24}):

$$q_{14} - q_{24} = 2\alpha \quad \textbf{4-39}$$

Rank 5: Reliability + Risks (*S_{24}*) was *moderately preferred* over Security of supply + Reliability (*S_{12}*):

$$q_{24} - q_{12} = 3\alpha \quad \textbf{4-40}$$

Rank 6: Security of supply + Reliability (*S_{12}*) was *extremely preferred* over Referendum (*S_0*):

$$q_{12} - q_0 = 6\alpha \quad \textbf{4-41}$$

By substituting Eqn 4-36 into Eqn 4-27, the following preference relationship between q_{34}, q_{13} is obtained:

$$q_{34} - q_{13} = \left(\phi_3 + \phi_4 - \frac{1}{2}(I_{13} + I_{14} + I_{23} + I_{24})\right)$$

$$- \left(\phi_1 + \phi_3 - \frac{1}{2}(I_{12} + I_{14} + I_{23} + I_{34})\right) = 4\alpha$$

$$q_{34} - q_{13} = \phi_4 - \phi_1 - \frac{1}{2}(-I_{12} + I_{13} + I_{24} - I_{34}) = 4\alpha \quad \textbf{4-42}$$

The process of identify the interaction indices (*I_{ij}*) is illustrated in Figure 4.21.

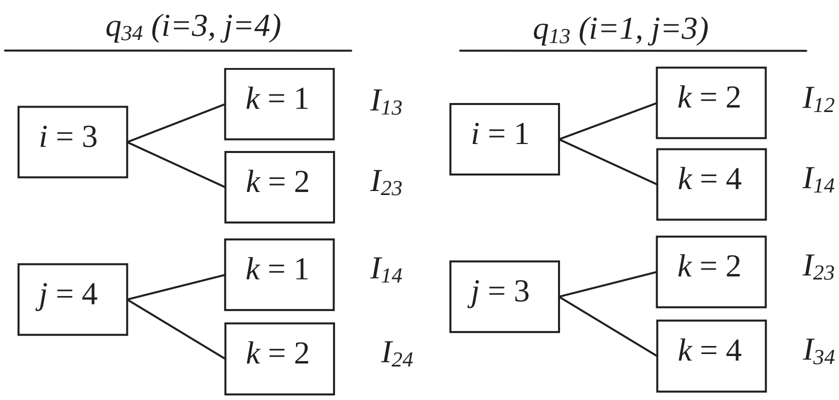


Figure 4.21 Illustrate Eqn 4-27 for the preference relation Eqn 4-42

By substituting Eqn 4-37 into Eqn 4-27, the following preference relationship between q_{13}, q_{23} is obtained:

$$q_{13} - q_{23} = \phi_1 - \phi_2 - \frac{1}{2}(-I_{13} + I_{14} + I_{23} - I_{24}) = 3\alpha \quad \textbf{4-43}$$

By substituting Eqn 4-38 into Eqn 4-27, the following preference relationship between q_{23}, q_{14} is obtained:

$$q_{23} - q_{14} = \phi_2 + \phi_3 - \phi_1 - \phi_4 = 3\alpha \qquad \textbf{4-44}$$

By substituting Eqn 4-39 into Eqn 4-27, the following preference relationship between q_{14}, q_{24} is obtained:

$$q_{14} - q_{24} = \phi_1 - \phi_2 - \frac{1}{2}(I_{13} - I_{14} - I_{23} + I_{24}) = 2\alpha \qquad \textbf{4-45}$$

By substituting Eqn 4-40 into Eqn 4-27, the following preference relationship between q_{24}, q_{12} is obtained:

$$q_{24} - q_{12} = \phi_4 - \phi_1 - \frac{1}{2}(I_{12} - I_{13} - I_{24} + I_{34}) = 2\alpha \qquad \textbf{4-46}$$

By substituting Eqn 4-41 into Eqn 4-27, the following preference relationship between q_{12}, q_0 is obtained:

$$q_{12} - q_0 = \phi_1 + \phi_2 - \frac{1}{2}(I_{13} + I_{14} + I_{23} + I_{24}) = 6\alpha \qquad \textbf{4-47}$$

<u>Step 5. Determine Shapley and Interaction indices</u>

The ten preference equations obtained from steps 2 (Eqn 4-32 to 4-35) and from Step 4 (Eqn 4-42 to 4-47) in conjunction with the condition $\phi_1 + \phi_2 + \phi_3 + \phi_4 = 1$ formed a system of equations which can be expressed by the following matrix in the form of *Ax* (Figure 4.22).The matrix is formed by taking the coefficient for each term $(\phi_1, \phi_2, \phi_3, \phi_4, I_{12}, I_{13}, I_{14}, I_{23}, I_{24}, I_{34}, h)$ to form A.

$$\begin{array}{ccccccccccc} \phi_1 & \phi_2 & \phi_3 & \phi_4 & I_{12} & I_{13} & I_{14} & I_{23} & I_{24} & I_{34} & h \end{array}$$

$$\begin{pmatrix} 0 & 0 & 1 & -1 & 0 & -0.5 & 0.5 & -0.5 & 0.5 & 0 & -2 \\ -1 & 0 & 0 & 1 & 0.5 & 0.5 & 0 & 0 & -0.5 & -0.5 & -3 \\ 1 & -1 & 0 & 0 & 0 & -0.5 & -0.5 & 0.5 & 0.5 & 0 & -3 \\ 0 & 1 & 0 & 0 & -0.5 & 0 & 0 & -0.5 & -0.5 & 0 & -2 \\ -1 & 0 & 0 & 1 & 0.5 & -0.5 & 0 & 0 & -0.5 & 0.5 & -4 \\ 1 & -1 & 0 & 0 & 0 & 0.5 & -0.5 & -0.5 & 0.5 & 0 & -3 \\ -1 & 1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -3 \\ 1 & -1 & 0 & 0 & 0 & -0.5 & 0.5 & 0.5 & -0.5 & 0 & -2 \\ -1 & 0 & 0 & 1 & -0.5 & 0.5 & 0 & 0 & 0.5 & -0.5 & -2 \\ 1 & 1 & 0 & 0 & 0 & -0.5 & -0.5 & -0.5 & -0.5 & 0 & -6 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \times \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ I_{12} \\ I_{13} \\ I_{14} \\ I_{23} \\ I_{24} \\ I_{34} \\ \alpha \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Figure 4.22 Matrix for the system of equation

The Shapley values and interaction indices were determined by solving the inverse matrix.

$\phi_1 = 0.15, \phi_2 = 0.04, \phi_3 = 0.52, \phi_4 = 0.28$

$I_{12} = -0.04, I_{13} = 0.04, I_{14} = -0.13, I_{23} = 0.04, I_{24} = -0.09, I_{34} = 0.09, \alpha = 0.04$

The preferences expressed by the other DMs are presented in F5.

Part B. Crisp MnF and normalise criteria scores

The same example from Section 4.3.1.3 Part B p.152 was applied.

4.3.4 Case 4. With judgement uncertainty and criteria interaction

In this case, the following assumptions were made:

- criteria were not assumed to be preferentially independent and thus the family of averaging aggregations[18] could not be applied. The Choquet integral was used instead as an aggregation tool to account for criteria interaction. (The problem of criteria interaction was explained in Section 2.5.4 p.54 and details about the Choquet integral are provided in Appendix D2.)
- judgement uncertainty was assumed and therefore fuzzy criteria weights and fuzzy criteria scores were determined.

This section explains how criteria interaction was considered in the preference modelling stage in conjunction with defuzzified criteria scores. Two outputs from this case were (Figure 4.23) Shapley and interaction index (criteria weights), and defuzzified criteria scores.

[18] Averaging operators treat criteria as preferentially independent.

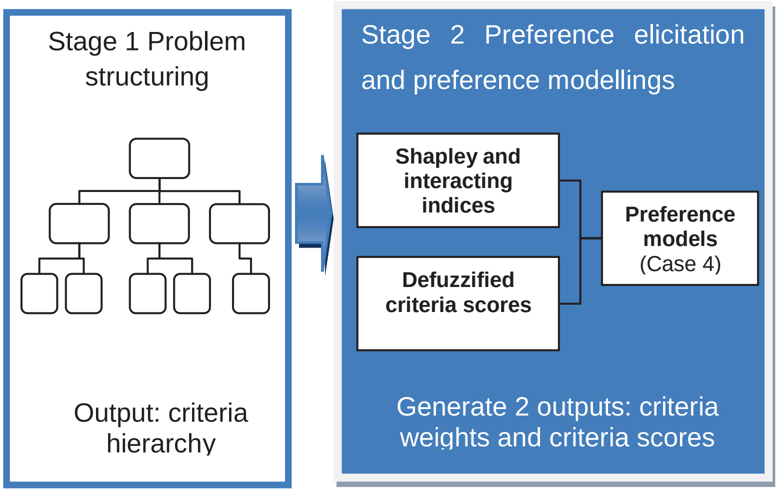


Figure 4.23 Decision support approach for Case 4

Part A. Shapley index and interaction index

The process of determining Shapley index and interaction index was the same as described in Section 4.3.30 p.167.

Part B. Fuzzy MnF and normalised criteria scores

Instead of using crisp criteria scores obtained from the crisp value functions according to the procedure described in Case 1 (Section 4.3.10 p.149), fuzzy MnF were used. The equation for obtain the 2-additive Choquet integral becomes Eqn 4-48 in which the crisp criteria scores x_i, x_j were replaced by defuzzified criteria scores x_i^d, x_j^d.

Although it is more appropriate to use the fuzzy criteria scores $\tilde{b}$ (obtained from the procedure described in Section 4.3.20 p.157) to represent $\tilde{x}$, the computational effort is much more demanding because the fuzzy criteria scores are not convex fuzzy sets[19] which is beyond the scope of this thesis to model. Furthermore, the computational effort is so complex which may deter usability. Nonetheless, the following procedure presented in this section is an innovative and simplified technique to incorporate fuzzy numbers to replace crisp criteria scores in the Choquet integral.

[19] A convex fuzzy set has segment of membership function is at least segmentally continuous and has the functional value µA(x) = 1 at precisely one element.

$$q = \sum_{i=1}^{n} \phi_i x_i^* - \frac{1}{2}\sum_{i=1}^{n} I_{ij}\left|x_i^* - x_j^*\right| \qquad \textbf{4-48}$$

To determine which fuzzy MnF types applied to the corresponding criteria, refer to Section 4.3.20 p.157. The following describe the procedure to obtain defuzzified criteria scores from the fuzzy MnF.

Step 1. Determine which linguistic values are activated $(\tilde{\boldsymbol{b}}_{\boldsymbol{tr}})$

The same procedure as described in Section 4.3.20 p.157 was applied.

Step 2. Obtain the appropriated fuzzy criteria scores $(\tilde{\boldsymbol{b}}_{\boldsymbol{atr}})$

The same procedure as described in Section 4.3.20 p.157 was applied.

Step 3. Defuzzify the appropriated fuzzy number

The fuzzy criteria score $(\tilde{b})$ is defuzzified by the centroid method (Eqn 4-49). The rational for the selection of the centroid method is given in Appendix D1.3.

$$x^d = \frac{\int \mu_{\tilde{b}}(x) \cdot x dx}{\int \mu_{\tilde{b}}(x) dx} \qquad \textbf{4-49}$$

The defuzzified criteria scores (x^d) are substituted back into Eqn 4-21 to obtain the aggregated alternative performance score. This is part of the aggregation process and is described in Chapter 5.

Case 4. Example

Part A. Shapley index and interaction index

The same example from Section 4.3.30 p.171 applied.

Part B. Fuzzy MnF and normalise criteria scores

The following illustrates the process of determining fuzzy criteria scores using the same example from Section 4.3.20 p.160. The first two steps were the same but an extra step (Step 3) was added to obtain the defuzzifed appropriated criteria score.

Step 3. Defuzzify the appropriated fuzzy criteria score

The fuzzy criteria score for the criterion risk for strategy A was defuzzified using the centroid method (Eqn 4-49) to derive a defuzzifed criteria score (x^d = 62) (Figure 4.24).

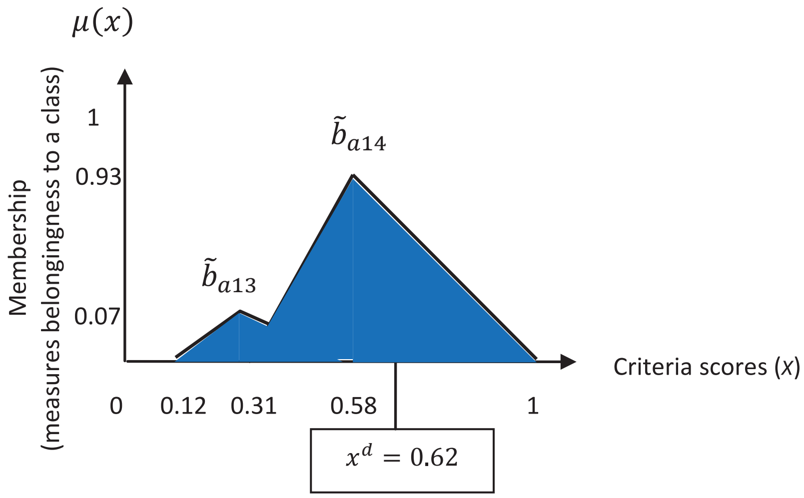


Figure 4.24 Defuzzified criteria score

4.4 Conclusions

This chapter presented the second stage of the decision support approach, preference elicitation and modelling. The previous chapter presented the first stage of the decision support approach (problem structuring phase) and the first shortcoming double counting was addressed. In this chapter, the other shortcomings (judgement uncertainty, criteria interaction and range sensitivity) were addressed.

- *Range sensitivity* – two novel techniques were introduced. One technique is to elicit criteria weights scores (mitigated value trade-off) and the other is to standardise criteria scores (mitigated normalising functions). They were developed to overcome the issue with range sensitivity. Mitigated value trade-off is a form of direct weight assignment with reference to a set of global measurable range or mitigated consequences. Mitigated normalising function is a normalising technique which utilises the elicited mitigation value trade-offs. These two techniques underpinned the four preference models which were developed subsequently.
- *Judgement uncertainty* – Fuzzy simple additive weighting was applied to model the imprecision associated with criteria scores and criteria weights. The criteria scores were determined using a fuzzy version of the mitigated normalising function, developed to address range sensitivity. This method was presented in case 2.
- *Criteria interaction* – Choquet integral was used as the underlying aggregation model to account for criteria interaction. This method is presented in case 3.

This chapter presented the techniques to address the four shortcomings (judgement uncertainty, criteria interaction and range sensitivity) in the preference elicitation and modelling stage. The techniques to aggregate the four preference models and the results are presented in the next chapter.

5 Aggregation

5.1 Introduction

This chapter presents the third stage of the decision support approach, aggregation (Figure 5.1). The first stage of the framework (problem structuring) was presented in Chapter 3 and the second stage of the framework (preference elicitation and modelling) presented in Chapter 4. This chapter explains the process of obtaining the aggregated results for the four preference models constructed from the second stage. The four preference models were developed as part of the Gold Coast Waterfuture case study. Each preference model had different assumptions in relation to the two identified shortcomings, judgement uncertainty and criteria interaction. Therefore, the processes of obtaining the aggregated results were different for the four preference models and so were the aggregated results.

As explained in Section 3.3.10 p.76, the calculated aggregated results were correlated to the observed aggregated results. The objective was to find out which preference model correlated the best to the observed global values, thereby exploring the influence of judgement uncertainty and criteria interaction. It is the purpose of this chapter to describe the different aggregation processes and to present the correlation analysis for showcasing the influence of judgement uncertainty and criteria interaction on the decision analysis.

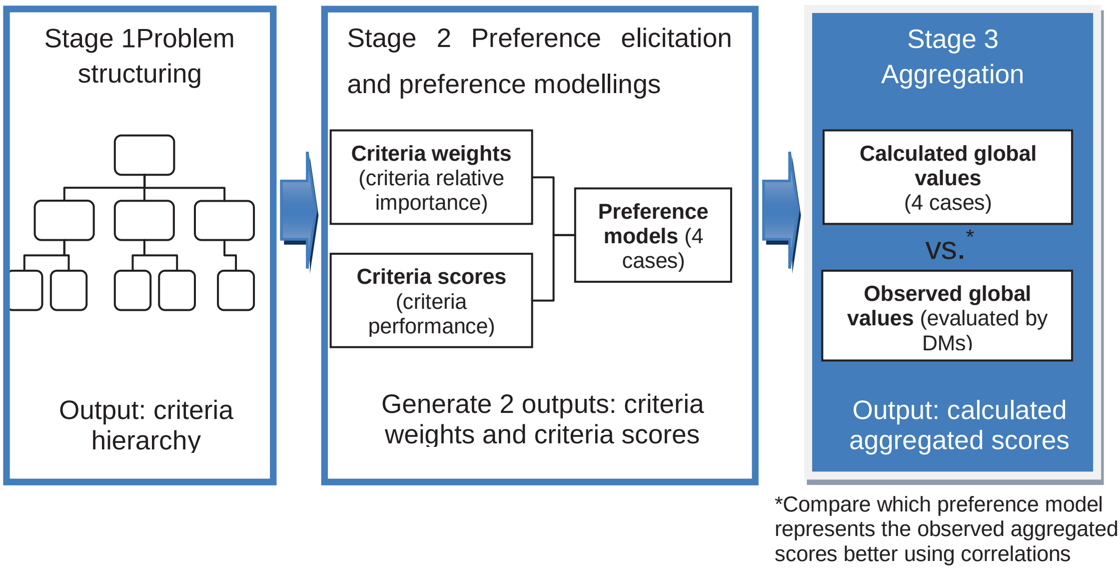


Figure 5.1 Schematic of decision support approach: Stage 3 Aggregation

In Section 5.2, the aggregation functions are reviewed to provide the basic concepts for this chapter. In Section 5.3, the procedures for conducting aggregation for each of the four cases are first presented, followed by examples to illustrate the procedures. The results of the aggregated preference models are presented at the end of cases. In Section 5.4, the results of the four cases are compared with each other. Correlations between the observed global values (given by the participants) and the calculated global values were taken (obtained from Section 5.3). The correlations indicate which calculated preference model represent the observed global values better. The structure of Chapter 5 is shown in Figure 5.2.

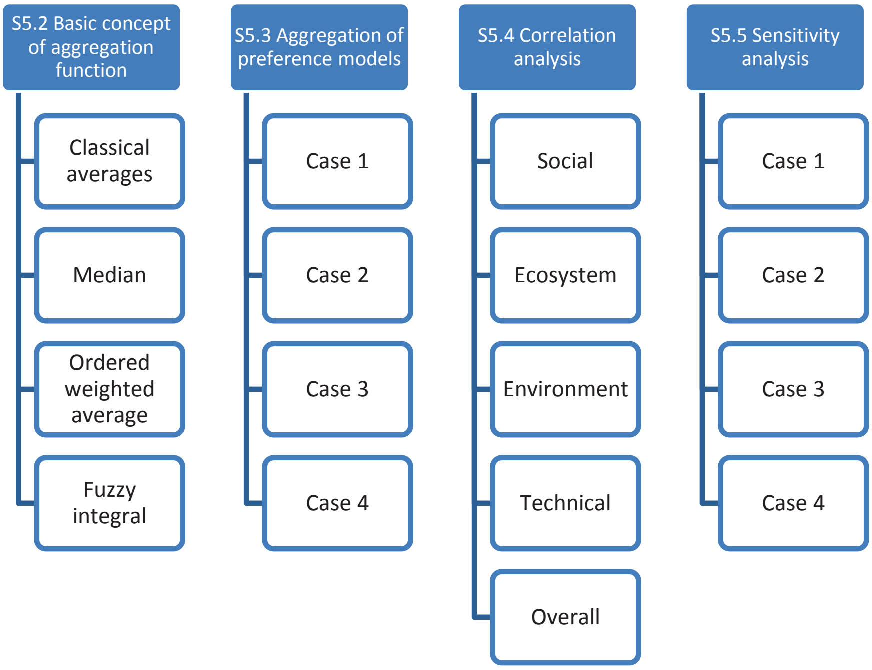


Figure 5.2 Structure of Chapter 5

5.2 Basic concept of aggregation function

The function of aggregation can be described as follows:

$$v(x) = F(x_1, \dots, x_n) \qquad \textbf{5-1}$$

where $v(x): X \to \mathbb{R}$ is the global value and $F: \mathbb{R}^n \to \mathbb{R}$ is an aggregation function. The argument x can be a vector of elements of size n. The argument can be a vector of criteria performance represented by n real values from the closed interval [0, 1]. An aggregation function combines the criteria performance to produce a real output value

$v(x)$ in [0, 1], commonly denoted as $F: [0,1]^n \to [0,1]$. An aggregation function used for this purpose is also referred to as a value function[20].

There are three main families of aggregation functions (Beliakov *et al.*, 2007). They are further described in Appendix D3:

- Conjunction aggregation representing the logical "AND" and disjunctive aggregation representing the logical "OR"
- Mixed aggregation
- Averaging aggregation.

5.2.1 Selected aggregation function: averaging

Comparisons between three aggregation families are detailed in Appendix D3.4. The main reason being that averaging function allows compensation to be made in between high and low input argument values and it does not fluctuate in between conjunctive and disjunctive behaviours Apart from the classical averages, in recent years, new types of averaging functions have emerged, such as ordered weighted averages (OWA) and fuzzy integrals (Sugeno, 1974; Yager, 1988). They are described as separate classes to the classical averages. Variations to the averaging functions are not limited to the following four groups: classical averages, median, ordered weighted averages and fuzzy integrals (Calvo *et al.*, 2002). These four groups of averaging functions are representative and sufficient to illustrate the variety (see Table 5.1).

[20] Value function denoted by $v(x)=F(x_1,\ldots,x_n)$ should not be confused with the normalising function f(x). Value function is the aggregation function to represent a DM's preference structure whereas normalising function is a function to normalise criteria scores.

Table 5.1 Averaging functions

Averaging function group	Type	Acronym
Classical averages	Weighted average	WA
	Arithmetic average	AA
	Harmonic average	HA
	Geometric average	GA
Median	Classic median	MED
	Weighted median	WMED
	Lukasiewicz median	LMED
	Product median	PMED
Ordered Weighted Averages	Yager's (1988) quantifier approach	OWAqua
	O'Hagan's (1988) orness approach	OWAorn
	Fullér and Majlender's (2001) entropy approach	OWAent
	Filev and Yager's (1998) exponential approach	OWAopt
	Filev and Yager's (1998) exponential approach	OWAper
Fuzzy integral	Choquet integral	CI

Classical averages

Classical averages include weighted average (WA), arithmetic average (AA), geometric average (GA), and harmonic average (HA) and are defined as follows:

- Weighted average (WA) is a function that associates each input with a weight to reflect the relative importance of the inputs. WA is one of the most widely used forms of aggregation. Given a set of weights $(w_1, w_2, \dots, w_n)$ and a set of normalised criteria scores $(x_1, x_2, \dots, x_n)$ where $\sum_{i=1}^{n} x_i = 1$, a weighted average (WA) operator is defined as:

$$WA(x) = (w_1x_1 + w_2x_2 + \cdots + w_nx_n) = \sum_{i=1}^{n} w_i x_i \qquad \textbf{5-2}$$

- Arithmetic average (AA) is the averaging function defined as:

$$AA(x) = \frac{1}{n}(x_1 + x_2 + \cdots + x_n) = \sum_{i=1}^{n} x_i \qquad \textbf{5-3}$$

- Geometric Average (GA) is the averaging function in which the additive component is replaced by multiplication:

$$GA(x) = \sqrt[n]{x_1 x_2 \dots x_n} = \left(\prod_{i=1}^{n} x_i\right)^{1/n} \qquad \textbf{5-4}$$

- Harmonic average (HA) is the averaging function defined as follows:

$$HA(x) = n\left(\sum_{i=1}^{n}\frac{1}{x_i}\right)^{-1} \quad \text{5-5}$$

Median

Median is the numerical number that separates the higher half of arguments from the lower half. The median of a finite number of arguments is the middle value of the ordered arguments in an increasing or decreasing order. There are four types of median applied in this research and they are described as follows:

- Classical median (MED) is defined as:

$$MED(x) = \begin{cases} \frac{1}{2}(x_i + x_{i+1}) & \text{if } n = 2i \text{ is even} \\ x_i & \text{if } n = 2i\text{-}1 \text{ is odd} \end{cases} \quad \text{5-6}$$

where *x* is non-increasing with elements $x_1 \geq x_2 \geq \cdots \geq x_n$.

- Weighted median aggregation (WMED) was introduced by Yager (1994). This method is useful in situations where the argument values are non-numerical. The argument values can be drawn from a scale with linear ordering while the weights are still numerical values. Let $x = (x_1, x_2, \ldots, x_n)$ be a set such that the elements x_i are ordered. Each argument x_i has two components $x_i^+,\ x_i^-$. These two components are defined as:

$$x_i^+ = (1 - w_i) * 100 + w_i x_i,$$
$$x_i^- = w_i x_i. \quad \text{5-7}$$

  where $w_i \in [0,1]$ are weights associated with x_i, i=1,…,n. The weighted median is computed by taking the median of all the x_i^+, x_i^-:

$$MED(x) = Median[x_1^+, x_1^-, x_2^+, x_2^-, \ldots, x_n^+, x_n^-] \quad \text{5-8}$$

Alternative forms of x_i^+, x_i^- by transforming x_i^+, x_i^- into t-norm (conjunction) and t-conorm (disjunction) respectively:

$$x_i^+ = S(w_i, x_i)$$
$$x_i^- = T(w_i, x_i)$$

Two common types of t-norms and t-conorms are applied to obtain two variations of the weighted median, Lukasiewicz median (LMED) and product median (PMED). These two types of transformation are commonly used and can be easily computed.

- LMED adopts the Lukasiewicz t-norm and t-conorm. The weighted median is computed by taking the median of all the x_i^+, x_i^- using Eqn 5-9.

$$x_i^+ = S(x_i, w_i) = \min(x_i + w_i, 1)$$
$$x_i^- = T(x_i, w_i) = \max(x_i + w_i - 1, 0) \quad \textbf{5-9}$$

- PMED adopts the product t-norm and t-conorm. The weighted median is computed by taking the median of all the x_i^+, x_i^- using Eqn 5-8.

$$S(x_i, w_i) = x_i + w_i - x_i w_i \quad \textbf{5-10}$$
$$T(x_i, w_i) = x_i w_i$$

Ordered weighted average

OWA developed by Yager (1988) has gained significant attention since its appearance twenty years ago and has a wide range of applications (Yager, 2002). OWA is useful in environments where positioning is more important, such as detecting objects using robots. Positioning is more important compared to the objects themselves because the task is to detect the objects closest to the robots. This differs from the classical averages in that the weight in OWA is not associated with a particular element but associated with a particular ordered position or values of the elements. OWA is defined as

$$OWA(x) = \sum_{i=1}^{n} w_{(i)} x_{(i)} \quad \textbf{5-11}$$

where $x_{(i)}$ is a vector with non-increasing elements $x_{(1)} \geq x_{(2)} \geq \cdots \geq x_{(n)}$ and (i) is the index of the ordering position.

The prime task in applying OWA is to determine the OWA weights. There are many methods of obtaining weights for the OWA operator (Xu, 2005). Four established methods are applied in this research：

- Yager’s (1988) quantifier approach (OWAqua)
- O’Hagan’s (1988) orness approach (OWAorn)

- Fullér and Majlender's (2001) entropy approach (OWAent)
- Filev and Yager's (1998) exponential approach (OWAopt and OWAper).

Yager's (1988) quantifier is defined as

$$w_i = Q\left(\frac{i}{n}\right) - Q\left(\frac{i-1}{n}\right), i = 1, \dots, n \qquad \text{5-12}$$

where Q_α is a regular non-degreasing quantifier $Q_\alpha = r^\alpha, \alpha \geq 0$ and α is a pre-determined index to fit the observed aggregation. This method is conveniently denoted as OWAqua.

O'Hagan's (1988) used two characterising measures called the orness measures (Eqn5-13) and the dispersion measure (Eqn 5-14) developed by Yager (1988) to generate the OWA weights based a constrained optimisation problem. The sets of OWA weights for various levels of orness can be found in O'Hagan. This method is conveniently denoted as OWAorn.

$$orness(w) = \frac{1}{n-1}\sum_{i=1}^{n}(n-i)w_i \qquad \text{5-13}$$

$$dispersion(w) = -\sum_{i=1}^{n} w_i ln(w_i) \qquad \text{5-14}$$

Fullér and Majlender's (2001) used Lagrange functions to solve O'Hagan's optimisation problem and obtained the following equations for deriving OWA weights. This method involves a predetermined orness level (σ). First, $w_{(1)}$ is determined by solving Eqn 5-15 and the obtained $w_{(1)}$ is substituted into Eqn 5-16 to obtain $w_{(n)}$. The obtained $w_{(n)}$ are substituted into Eqn 5-17 to obtain other OWA weights $w_{(i)}$. This method is conveniently denoted as OWAent.

$$w_{(1)}\left[(n-1)\sigma + 1 - nw_{(1)}\right]^n = \left((n-1)\sigma\right)^{n-1}\left[\left((n-1)\sigma - n\right)w_{(1)} + 1\right] \qquad \text{5-15}$$

$$w_{(n)} = \frac{\left((n-1)\sigma -\right)w_{(1)} + 1}{(n-1)\sigma + 1 - nw_{(1)}} \qquad \text{5-16}$$

$$w_{(i)} = \sqrt[n-1]{w_{(1)}^{n-i} w_{(n)}^{i-1}} \qquad \text{5-17}$$

Filev and Yager (1998) provided a simpler relationship between the orness degree and the OWA weights using an exponential smoothing technique. Two types of OWA weights using the exponential smoothing technique were introduced, optimistic and pessimistic. This method involves a predetermined alpha (α) level which is defined by the orness level specified. The optimistic method is conveniently denoted as OWAopt and the pessimistic method is denoted as OWApes.

The OWA weights using the *optimistic method* are defined as:

$$w_1 = \alpha, \tag{5-18}$$

$$w_i = w_{i-1}(1 - w_{i-1}), \tag{5-19}$$

$$w_n = \frac{w_{n-1}(1 - w_1)}{w_1}. \tag{5-20}$$

The OWA weights using the *pessimistic method* are defined as:

$$w_1 = \frac{w_2(1 - w_n)}{w_n}, \tag{5-21}$$

$$w_i = w_{i+1}\alpha, \tag{5-22}$$

$$w_n = (1 - \alpha). \tag{5-23}$$

Fuzzy integrals

The fuzzy integral is an aggregation function which aggregates arguments with interaction. It takes into account not only the importance of the individual argument (as in the classical averages) and their relative position (as in OWA), but also the influence of the arguments as a group. There are two main types of fuzzy integrals: Choquet integral and Sugeno integral. The Choquet integral is more applicable if the input arguments are measured in cardinal scales (numerical values) and the Sugeno integral is more applicable if the input arguments are measured in ordinal scales (ranks). The Choquet integral is more suitable for application in this research because the input values are numerical values. Details about the Choquet integral are provided in Appendix D2.

5.3 Aggregation of preference models

This section explains the process of obtaining the *calculated aggregated results* for the four preference models described in Chapter 4. The processes of obtaining the calculated aggregated results were different for the four preference models. To appreciate the differences, the aggregation process for each preference model is first described, followed by an example to illustrate the procedure. The calculated aggregated results from each preference model were correlated to the *observed global values* given by the participants in the case study. They became the observed aggregated results. The objective was to find out which preference model correlated the best to the observed global values, thereby exploring the influence of judgement uncertainty and criteria interaction. The results from the correlation analysis are presented in Section 5.4. This section is concerned with the calculated aggregated results.

In Table 4.10, the author indicated that for the preference models without criteria interaction (Cases 1 and 2), the family of averaging aggregation functions applied. For the preference models that assumed criteria interaction (Cases 3 and 4), the author specified that Choquet integral (a special class of averaging function) applied. They are briefly summarised again in Table 5.2.

Table 5.2 Aggregation function for the four cases

Assumptions	Description	Aggregation function
No criteria interaction	Case 1	Classical averages, median, ordered weighted averages
	Case 2	Classical averages
Criteria interaction	Case 3	Choquet integral
	Case 4	Choquet integral

5.3.1 Case 1. Without judgement uncertainty and criteria interaction

The following assumptions were made in Case 1:

- preferential independency between criteria was assumed which enabled the family of averaging aggregation operators to be adopted as the value functions
- judgement uncertainty was not assumed and therefore crisp criteria weights and normalised crisp criteria scores were determined.

In Section 4.3.1 p.148, the preference model for Case 1 is presented. Two output parameters were obtained from the preference models in Stage 2 (Figure 5.3):

- crisp criteria weights
- normalised crisp criteria scores.

The normalised crisp criteria scores are presented in Appendix F2.

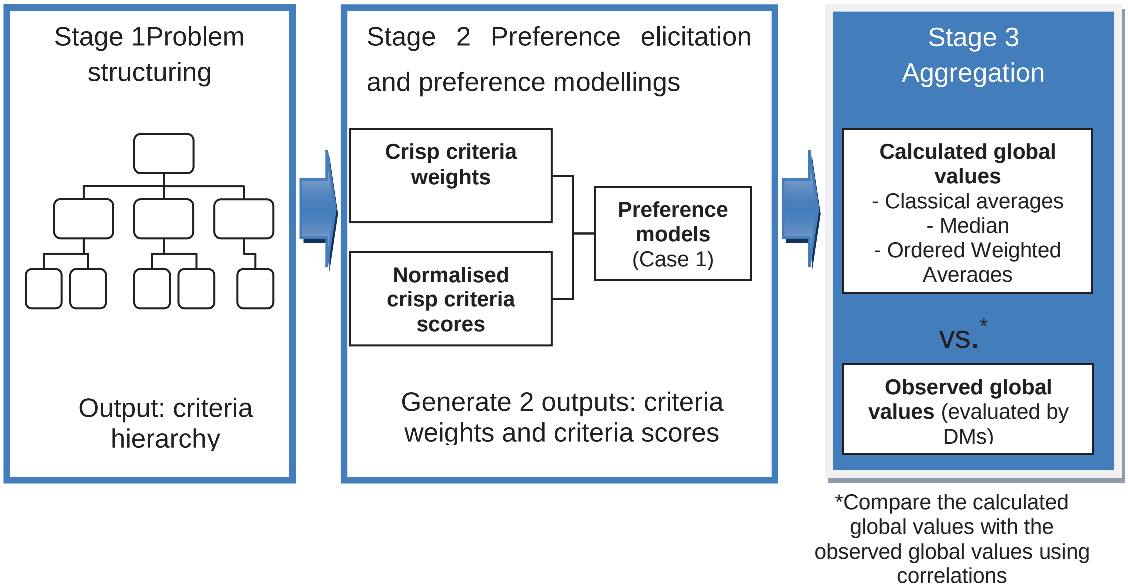


Figure 5.3 Decision support approach for Case 1

Stage 3 of the decision support approach is concerned with aggregating the two parameters (crisp criteria weights and normalised crisp criteria scores) to produce the calculated global values for the alternatives. Since criteria interaction was not considered, three different groups of averaging function (classical averaging, median and OWA) were applied in this case. See Table 5.1 for the full list of aggregation functions under each group. Each of the three averaging function groups has its own specific implication. Classical averaging considers the importance of individual criteria, median considers the middle value and OWA considers the relative ranking of the weighted criteria scores. The different types of averaging functions are introduced in Appendix D3.3 and are not repeated here. An example is given in the following to illustrate the process of applying the different averaging functions.

Example

Consider the same example used in Chapter 4 concerning the technical criteria given by the water manager M2. The normalised criteria scores and the associated criteria weights obtained from the preference model (Section 4.3.10 p.151) are presented in Table 5.3. The task was to calculate the aggregated results using the two input parameters, normalised criteria scores and criteria weights.

Table 5.3 Normalised criteria scores and criteria weights

	Normalised criteria score (*x*)					Weight (w)
Strategy	**A**	**B**	**C**	**D**	**E**	
Security of supply (c_6)	38	34	34	50	56	0.5
Reliability (c_7)	58	76	64	62	72	0.5
Flexibility (c_8)	81.50	76.50	81.50	80	83.50	0
Risks (c_9)	78	84.50	85	81.50	76	0

The following presents the global values using the three groups of averaging functions (classical average, median and OWA) as the value functions $v(x)$.

Classical averaging

Using Eqn 5-3, the global value for strategy A given by weighted averages was

$$v_{WA} = 38 * 0.5 + 58 * 0.5 + 81.5 * 0 + 78 * 0 = 48$$

Using Eqn 5-4, the global value for strategy A given by arithmetic averages was

$$v_{AA} = (38 + 58 + 81.5 + 78)/4 = 64$$

Using Eqn 5-5, the value for strategy A given by geometric averages was

$$v_{GA} = \sqrt[4]{(38 \times 58 \times 81.5 \times 78)} = 61$$

Using Eqn 5-6, the value for strategy A given by harmonic averages is

$$v_{HA} = 4 \times \left(\frac{1}{38} + \frac{1}{58} + \frac{1}{81.5} + \frac{1}{78}\right)^{-1} = 58$$

The results for the other strategies are presented in Table 5.4.

Table 5.4 Classical averages for technical criteria evaluated by water manager M2

	Strategy				
Criteria score	**A**	**B**	**C**	**D**	**E**
Weighted average	48	55	49	56	64
Average	64	68	66	68	72
Geometric average	61	64	62	67	71
Harmonic average	58	59	58	66	70

Median

Classic Median

The vector of normalised criteria scores for strategy A was $x = \{38, 58, 81.5, 78\}$ (Table 5.3). This vector was re-ordered in a non-increasing manner $x = \{81.5, 78, 58, 38\}$. To obtain the median of the re-ordered vector, Eqn 5-6 was applied. The middle values of the ordered vector were $x_{(2)} = 78$ and $x_{(3)} = 58$. The average of these two values was the global value for strategy A.

$$v_{MED} = \frac{1}{2}(58 + 78) = 68$$

Weighted Median

To obtain the weighted median, a similar process to the classical median was applied. Each argument x_i was transformed into two components x_i^+, x_i^- using Eqn 5-7:

$$x_6^+ = (1 - 0.5) \times 100 + 0.5 \times 38 = 69, \qquad x_6^- = 0.5 \times 38 = 19,$$

$$x_7^+ = (1 - 0.5) \times 100 + 0.5 \times 58 = 79, \qquad x_7^- = 0.5 \times 58 = 29,$$

$$x_8^+ = (1 - 0) \times 100 + 0 \times 81.5 = 100, \qquad x_8^- = 0 \times 58 = 0,$$

$$x_9^+ = (1 - 0) \times 100 + 0 \times 78 = 100, \qquad x_9^- = 0 \times 78 = 0.$$

The x_i^+, x_i^- values were arranged in a non-increasing order and the median were taken from the ordered vector to obtain the global value.

$$x = \{100, 100, 79, \mathbf{69}, \mathbf{29}, 19, 0, 0\}$$

$$v_{WMED} = \frac{1}{2}(69 + 29) = 49$$

Lukasiewicz Median

The process of obtaining the Lukasiewicz median was similar to the weighted median. The transformation of the input argument value x_i was obtained using the Lukasiewicz t-norm (S) and t-conorm (T) (Eqn 5-9). The transformed S_i and T_i are:

$$S_6 = \min(0.5 + 38/100\,, 1) * 100{=}88, \qquad T_6 = \max(0.5 + 38/100 - 1{,}0) * 100 = 0,$$
$$S_7 = \min(0.5 + 58/100\,, 1) * 100 = 100, \qquad T_7 = \max(0.5 + 58/100 - 1{,}0) * 100 = 8,$$
$$S_8 = \min(0 + 81.5/100\,, 1) * 100 = 82, \qquad T_8 = \max(0 + 81.5/100 - 1{,}0) * 100 = 0,$$
$$S_9 = \min(0 + 78/100\,, 1) * 100 = 78, \qquad T_9 = \max(0 + 78/100 - 1{,}0) * 100 = 0.$$

The S_i, T_i values were arranged in a non-increasing order and the median was taken from the ordered vector to obtain the global value for strategy A.

$$x = \{100, 88, 82, \mathbf{78}, \mathbf{8}, 0, 0, 0\}$$
$$v_{LMED} = \frac{1}{2}(78 + 8) = 43$$

Product Median

The transformation of the input argument value x_i was obtained using the Product t-norm (S) and t-conorm (T) (Eqn 5-10). The transformed S_i and T_i are presented as follow:

Using Eqn 5-11, the value for strategy A given by PMED is:

$$S_6 = (0.5 + 0.38 - 0.5 \times 0.38) \times 100 = 69 \qquad T_6 = (0.5 \times 38/100) \times 100 = 19$$
$$S_7 = (0.5 + 0.58 - 0.5 \times 0.58) \times 100 = 79 \qquad T_7 = (0.5 \times 58/100) \times 100 = 29$$
$$S_8 = (0 + 0.815 - 0 \times 0.815) \times 100 = 81.5 \qquad T_8 = (0 \times 81.5/100) \times 100 = 0$$
$$S_9 = (0 + 0.78 - 0 \times 0.78) \times 100 = 78 \qquad T_9 = (0 \times 78/100) \times 100 = 0$$

The S_i, T_i values were arranged in a non-increasing order and the median was taken from the ordered vector to obtain the global value for strategy A.

$$x = \{81.5, 79, 78, \mathbf{69}, \mathbf{29}, 19, 0, 0\}$$
$$v_{PMED} = \frac{1}{2}(69 + 29) = 49$$

A summary of the global values using the family of median aggregations is shown in Table 5.5. The summary only shows the global values for technical criteria.

Table 5.5 Aggregated scores using median for technical criteria evaluated by water manager M2

	Strategy *v(x)*				
Technical Criteria	**A**	**B**	**C**	**D**	**E**
Median (MED)	68	76	73	71	74
Weighted Median (WMED)	49	53	50	53	57
Product Median (PMED)	43	51	48	46	49
Lukasiewicz Median (LMED)	49	53	50	53	56

Ordered weighted averages

In contrast to classical averages, the weights for OWA are associated with the ordered position of the criteria and not associated with the criteria's relative importance. To obtain OWA weights, the first step is to arrange the input argument values into a non-increasing order. The following table (Table 5.6) shows the re-ordered criteria scores $x_{(1)} \geq x_{(2)} \geq x_{(3)} \geq x_{(4)}$ and the criteria weights associated with respect to the ordered position.

Table 5.6 Ordered technical criteria

	Strategy					Weights
Ordered position	**A**	**B**	**C**	**D**	**E**	$w_{(i)}$
Ordered position 1 $x_{(1)}$	81.5	84.5	85	81.5	83.5	0.5
Ordered position 2 $x_{(2)}$	78	76.5	81.5	80	76	0.5
Ordered position 3 $x_{(3)}$	58	76	64	62	72	0
Ordered position 4 $x_{(4)}$	38	34	34	5	56	0

Five different methods of obtaining OWA weights are outlined in Section 5.2.1 0 p.190. The OWA weights were obtained based on a predetermined orness (σ) of 0.6. This orness level signifies a given aggregation function's relative difference to the maximum function. An orness level of 0.5 reduces the OWA function to the classical average, at an orness level of 1 the function becomes maximum and at an orness level of 0, the function becomes minimum. This level of orness ($\sigma = 0.6$) was selected as an approximation to indicate a closer relative difference to the maximum function.

Yager's (1988) quantifier approach

The OWA weights are associated with the quantifier Q_α. The quantifier is associated with an index α which approximates the experts' preference as much as possible. To adhere strictly to Yager's quantifier, the index α was required for each individual participant. To minimise the computation burden and without loss of generality, let us assume $\alpha = 1.2$. The following demonstrates how the OWA weights are derived using the quantifier approach (Eqn 5-12) for n = 4:

$$w_{(1)} = \left(\frac{1}{4}\right)^{1.2} - (0)^{1.2} = 0.19; w_{(2)} = \left(\frac{2}{4}\right)^{1.2} - \left(\frac{1}{4}\right)^{1.2} = 0.25;$$

$$w_{(3)} = \left(\frac{3}{4}\right)^{1.2} - \left(\frac{2}{4}\right)^{1.2} = 0.27; w_{(4)} = (1)^{1.2} - \left(\frac{3}{4}\right)^{1.2} = 0.29.$$

O'Hagan's (1988) orness approach

The OWA weights using O'Hagan's orness method were derived and presented in O'Hagan (1988). For $n = 4$ and orness $\sigma = 0.6$, the OWA weights are:

$$w_{(1)} = 0.35; w_{(2)} = 0.27; w_3 = 0.21; w_{(4)} = 0.17.$$

Fullér and Majlender's (2001) entropy approach

Give that $n = 4$ and orness $\sigma = 0.6$, $w_{(1)}$ is first determined by solving Eqn 5-15:

$$w_{(1)}\left[3 \times 0.6 + 1 - 4w_{(1)}\right]^4 = (3 \times 0.6)^3\left[(3 \times 0.6 - 4)w_{(1)} + 1\right]$$

$$w_{(1)} = 0.25$$

The obtained $w_{(1)}$ is substituted into Eqn 5-17 to obtain $w_{(4)}$.

$$w_{(4)} = \frac{(3 \times 0.6 - 4) \times 0.25 + 1}{3 \times 0.6 + 1 - 4 \times 0.25} = 0.25$$

The obtained $w_{(4)}$ are substituted into Eqn 5-18 to obtain other weights $w_{(2)}$ and $w_{(3)}$.

$$w_{(2)} = \sqrt[3]{w_{(1)}^2 w_{(n)}^1} = \sqrt[3]{(0.25)^3} = 0.25$$

$$w_{(3)} = \sqrt[3]{w_{(1)}^1 w_{(n)}^2} = \sqrt[3]{(0.25)^3} = 0.25$$

Filev and Yager's (1998) optimistic OWA

In this approach, an index α that associates with the orness level is utilised to define the OWA weights. Give that $n = 4$ and orness $\sigma = 0.6$, the corresponding α for the optimistic OWA is 0.4. The relationship between the index α and the orness level σ is presented in Filev and Yager's (1998). The optimistic OWA weights are derived using

Eqn 5-18 for $w_{(1)}$, Eqn 5-19 for $w_{(2)}$, $w_{(3)}$ and Eqn 5-20 for $w_{(4)}$. They are shown as follows:

$$w_{(1)} = 0.4;\ w_{(2)} = 0.4(1 - 0.4) = 0.24;$$

$$w_{(3)} = 0.24(1 - 0.4) = 0.14; w_{(4)} = \frac{0.144(1 - 0.4)}{0.4} = 0.22.$$

Filev and Yager's (1998) pessimistic OWA

The procedure to determine pessimistic OWA weights is similar to that for optimistic OWA except that the relationship between the index α and the orness level σ is different. Give that $n = 4$ and orness $\sigma = 0.6$, the corresponding α for the optimistic OWA is 0.75 (see Filev and Yager's (1998)). The optimistic OWA weights are derived using Eqn 5-21 for $w_{(1)}$, Eqn 5-22 for $w_{(2)}$, $w_{(3)}$ and Eqn 5-23 for $w_{(4)}$. They are shown as follows:

$$w_{(1)} = \frac{0.14(1 - 0.25)}{0.25} = 0.42;\ w_{(2)} = 0.19 \times 0.75 = 0.14;$$

$$w_{(3)} = 0.25 \times 0.75 = 0.19; w_{(4)} = (1 - 0.75) = 0.25.$$

The derived OWA weights using the five different methods are presented in Table 5.7.

Table 5.7 Ordered weighted average (OWA) weights using the five OWA methods

Ordered weights	Yager's Quantifier (OWAqua)	O'Hagan's Orness (OWAorn)	Fuller & Majlender's Entropy (OWAent)	Filev & Yager's Optimistic (OWAopt)	Filev & Yager's Pessimistic (OWApes)
$w_{(1)}$	0.19	0.35	0.25	0.40	0.42
$w_{(2)}$	0.25	0.27	0.25	0.24	0.14
$w_{(3)}$	0.27	0.21	0.25	0.14	0.19
$w_{(4)}$	0.29	0.17	0.25	0.22	0.25

These OWA weights are substituted back into Eqn 5-11 to obtain the global values for the different alternatives. For example, the OWA weights using Yager's quantifier approach are $w = (0.19, 0.25, 0.27, 0.29)$ (Table 5.7) and the normalised criteria scores for strategy A evaluated by the water manager M2 are $x = \{81.5, 78, 58, 38\}$ (Table 5.6). They are substituted into Eqn 5-11 to obtain the global values as follows:

$$v = 0.19 \times 81.5 + 0.25 \times 78 + 0.27 \times 58 + 0.29 \times 38 = 62.$$

The global values using the five OWA for technical criteria are presented in Table 5.8. The observed global values given by the participants are also presented in Table 5.8 for illustration. The correlation between the calculated global values and the observed global values are discussed in Section.

Results

The results are presented in the format of scatterplots in Appendix F4. The scatterplots show the relationships between the observed global values by the participants and the calculated global values by the aggregation functions. The observed global values given by the participants can be found in Appendix F3.

Table 5.8 Global values using Ordered Weighted Averages (OWA) for technical criteria evaluated by water manager M2

	Strategy				
Criteria score	**A**	**B**	**C**	**D**	**E**
Yager's OWA Quantifier (OWAqua)	62	65	64	67	70
O'Hagan's OWA Orness (OWAorn)	68	72	71	72	74
Fuller & Majlender's OWA Entropy (OWAent)	64	68	66	68	72
Filev & Yager's OWA Optimistic (OWAopt)	68	70	70	72	74
Filev & Yager's OWA Pessimistic (OWAper)	66	69	68	70	73
Observed global values	70	50	90	80	60

5.3.2 Case 2. With judgement uncertainty

The following assumptions were made in Case 2:

- preferential independency between criteria was assumed, which enabled the family of averaging aggregation operators to be adopted as the value functions
- judgement uncertainty was assumed and therefore fuzzy criteria weights and fuzzy criteria scores were determined.

At the aggregation stage, it was assumed that the following two parameters are obtained from the case 2 preference modelling stage (Figure 5.4). The procedure for obtaining the follow two parameters are outlined in Section 4.3.2 p.153:

- fuzzy criteria weights $(\tilde{a})$
- appropriated fuzzy criteria scores $(\tilde{b})$.

Aggregation in modified fuzzy simple additive weighting

Recall that from Section 4.3.2 p.153 a modified FSAW was developed that was based on Bonissone's (1979) approach[21]. In Chapter 4 under the preference modelling stage, fuzzy criteria weights were obtained and the fuzzy criteria scores were appropriated on the basis of the activated membership degrees. Here, the author introduces the remaining parts of the FSAW procedure, which is to aggregate the fuzzy criteria weights and the appropriated fuzzy criteria scores.

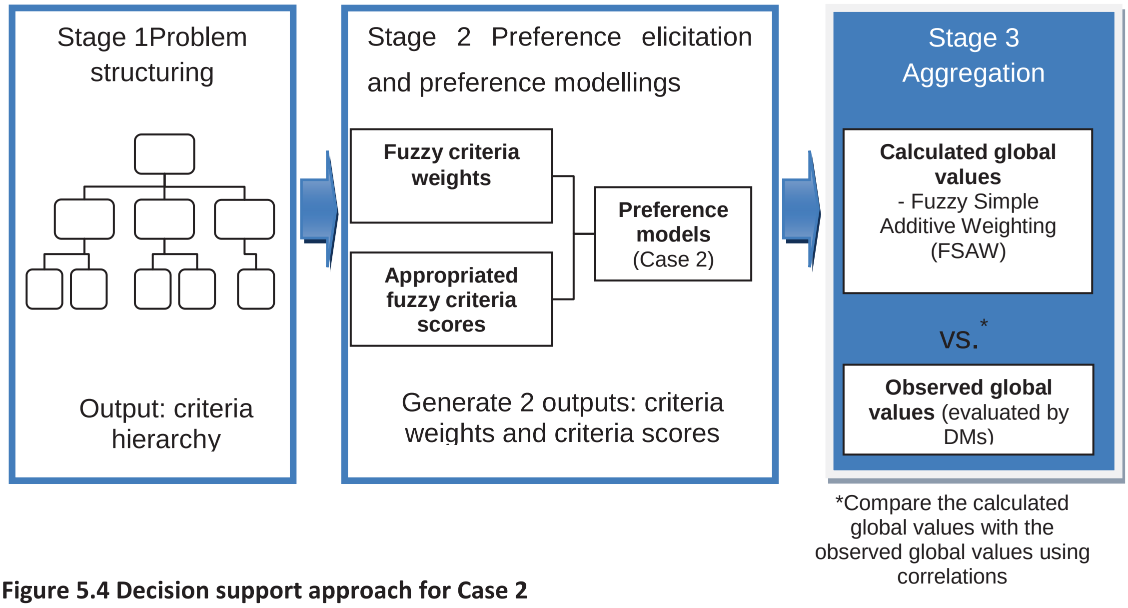


Figure 5.4 Decision support approach for Case 2

The value function for FSAW was defined the same as for simple additive weighting (Eqn 2.1). Instead of using crisp values for the criteria weights and criteria scores, both w_i and x_i were defined as fuzzy numbers $\widetilde{w}_i = \{w_i, \mu(w_i)\}$ and $\tilde{x}_{ij} = \{x_i, \mu(x_i)\}$ where $\mu(w_i)$ and $\mu(x_i)$ were the corresponding membership degrees for w_i and x_i respectively.

$$v_{FSAW} = (\widetilde{w}_1\tilde{x}_1 + \widetilde{w}_2\tilde{x}_2 + \cdots + \widetilde{w}_n\tilde{x}_n) = \sum_{i=1}^{n} \widetilde{w}_i\tilde{x}_i \qquad \textbf{5-24}$$

The full procedure of the modified FSAW can be outlined in the following steps:

- **Step 1 & Step 2:** described in Section 4.3.2 p.153 (Stage 2 Preference modelling)
- **Step 3 & Step 4:** described in the following (Stage 3 Aggregation).

[21] Rationale for selection is given in Section 2.8.1.1 A.

The following firstly gives a brief summary of Step 1 and Step 2, followed by a detailed explanation of Step 3 and Step 4.

Step 1. Determine activated linguistic values for both criteria weights and scores

The activated linguistic values $(\tilde{a}_s)$ for fuzzy criteria weights were determined from the mitigated value trade-offs expressed by DMs. The chosen criteria weights specified which mitigated normalising function (MnF) would be applied. The activated linguistic values from the selected MnF were determined to represent the fuzzy criteria scores $(\tilde{b}_{tr})$.

Step 2. Obtain the appropriate fuzzy scores and fuzzy weights

Instead of using the entire fuzzy numbers $(\tilde{a}_s)$ and $(\tilde{b}_{tr})$ to represent the activated linguistic values (as suggested in the Bonissone's (1979) approach), the fuzzy numbers were multiplied by the corresponding activated membership degrees $\mu_{\tilde{a}_s}(w)$ to obtain the appropriated fuzzy numbers $(\tilde{a}_{as})$ and $(\tilde{b}_{atr})$.

Step 3. Obtain the weighted scores $(\tilde{\boldsymbol{w}}_i\tilde{\boldsymbol{x}}_i)$

The appropriated fuzzy criteria weights $(\tilde{a}_{as})$ and the appropriated fuzzy criteria scores $(\tilde{b}_{atr})$ obtained from the previous step formed the outputs for Stage 2. They are multiplied to obtain the fuzzy weighted scores $(\tilde{z})$. Since there can be two $\tilde{a}_{as}$ and two $\tilde{b}_{atr}$ at the most, there are four possible combinations between these fuzzy criteria weights and fuzzy criteria scores to obtain the weighted scores $(\tilde{w}_i\tilde{x}_i)$. The four possible combinations are presented as follows:

$$\tilde{z}_1 = \tilde{a}_{as1} \cdot \tilde{b}_{atr1} \quad \textbf{5-25}$$

$$\tilde{z}_2 = \tilde{a}_{as1} \cdot \tilde{b}_{atr2} \quad \textbf{5-26}$$

$$\tilde{z}_3 = \tilde{a}_{as2} \cdot \tilde{b}_{atr1} \quad \textbf{5-27}$$

$$\tilde{z}_4 = \tilde{a}_{as2} \cdot \tilde{b}_{atr2} \quad \textbf{5-28}$$

To calculate the product between two fuzzy numbers, Zadeh's (1975) extension principle was used instead of the normal arithmetic. Zadeh's extension principle is defined as:

$$\mu_{\tilde{a}_{as}*\tilde{b}_{atr}} = \bigvee_{\tilde{a}*\tilde{b}} \left(\mu_{\tilde{a}_{as}}(w) \wedge \mu_{\tilde{b}_{atr}}(x)\right) \quad \text{5-29}$$

where $\mu_{\widetilde{w}_i}(w)$ and $\mu_{\tilde{x}_i}(x)$ are the membership degrees of $\tilde{a}_{as}$ and $\tilde{b}_{atr}$ respectively, the operation $\wedge$ is maximum and $\vee$ is minimum. The fuzzy arithmetic for production between $\tilde{a}$ and $\tilde{b}$ is denoted by "$*$" instead of "$\times$" which is the general arithmetic operation.

To apply the extension principle, first determine the interval of the product between the two fuzzy numbers. Let I_1 and I_2 be two interval numbers for two fuzzy number $\widetilde{w}$ and $\tilde{x}$. The intervals are defined by the ordered pairs of two real numbers, $I_1 = [\mathrm{a}, \mathrm{b}]$ and $I_2 = [\mathrm{c}, \mathrm{d}]$, where $a \leq b$ and $c \leq d$. The fuzzy summative operations between the two intervals are given as follows:

$$I_3 = [a, b] \times [c, d] = [min(ac, ad, bc, bd), max(ac, ad, bc, bd)], \quad \text{5-30}$$

where I_3 is the product interval.

Next determine the membership degree for each value in the product interval I_3. The extension principle is used to determine the membership degree of the product $\tilde{A} \times \tilde{B}$. To illustrate the process of applying the extension principle to obtain the product between two fuzzy numbers, an example is used (Ross, 2004). Consider two fuzzy numbers $\tilde{A}$ and $\tilde{B}$ in the form of $\left\{\frac{\mu_{\tilde{A}}(w_i)}{w_i}\right\}$ and $\left\{\frac{\mu_{\tilde{B}}(x_i)}{x}\right\}$ where $\mu_{\tilde{A}}(w_i)$ and $\mu_{\tilde{B}}(x_i)$ are the membership degrees and w_i and y_i are the corresponding real values:

$$\tilde{A} = \left\{\frac{0.2}{1} + \frac{1}{2} + \frac{0.7}{4}\right\} \text{ and } \tilde{B} = \left\{\frac{0.5}{1} + \frac{1}{2}\right\}.$$

The problem is to determine $\widetilde{V}$, which is the product of $\tilde{A}$ and $\tilde{B}$.

The intervals for $\tilde{A}$ and $\tilde{B}$ are $I_1 = [1,4]$ and $I_2 = [1,2]$ respectively. The interval of the product between $\tilde{A}$ and $\tilde{B}$ is

$$I_3 = [1, 4] \times [1,2] = [min(1,2,4,8), max(1,2,4,8)] = [1,8].$$

The extension principle is applied to obtain the membership degree for the corresponding real values in the interval, as shown in Table 5.9.

Table 5.9 Real values and the corresponding membership values for (a) $\tilde{A}$, (b) $\tilde{B}$

w_i	$\mu_{\tilde{A}}(w_i)$	x_i	$\mu_{\tilde{B}}(x_i)$
1	0.2	1	0.5
2	**1**	**2**	**1**
4	0.7		

The following table (Table 5.10) shows the different possible combinations between w_i and x_i to yield the product $v_i = w_i x_i$. The corresponding membership degree for w_i and x_i are also presented.

Table 5.10 Different combinations between w_i and x_i to yield the $w_i x_i$

$\tilde{A} \times \tilde{B}$	$\tilde{A}$		$\tilde{B}$	
$w_i x_i = v_i$	w_i	$\mu_{\tilde{A}}(w_i)$	x_i	$\mu_{\tilde{B}}(x_i)$
1	1	0.2	1	0.5
2	1	0.2	2	1
	2	1	1	0.5
4	2	1	2	1
	4	0.7	1	0.5
8	4	0.7	2	1

For the product $v = 1$, there is only combination between w and x that yields the product $(1 \times 1 = 1)$ (Table 5.10). The corresponding membership degrees for $w = 1$ and $x = 1$ are $\mu_{\tilde{A}}(1) = 0.2$ and $\mu_{\tilde{B}}(1) = 0.5$. The membership degree for the real value 1 for the product v is determined using the extension principle (Eqn 5-29). The minimum between the two corresponding membership degrees is taken:

$$\mu_{\tilde{V}}(1) = \mu_{\tilde{A}}(1) \wedge \mu_{\tilde{B}}(1) = 0.2 \wedge 0.5 = \min(0.2, 0.5) = 0.2$$

For the product $v = wx = 2$, there are two combinations between w and x that yield the product $v = 2$ (Table 5.10). Applying the extension principle (Eqn 5-30), the maximum between the two combinations is taken to yield the corresponding membership degree for $v = 2$:

$$\mu_{\tilde{V}}(2) = [\mu_{\tilde{A}}(1) \wedge \mu_{\tilde{B}}(2)] \wedge [\mu_{\tilde{A}}(2) \wedge \mu_{\tilde{B}}(1)] = [0.2 \wedge 1] \wedge [1 \wedge 0.5]$$

$$\mu_{\tilde{V}}(2) = \max[\min(0.2,1), \min(1,0.5)] = 0.5$$

The other corresponding membership degrees for $v = 2$ and $v = 8$ are determined in a similar fashion. The resulting product $\tilde{V}$ is:

$$\tilde{V} = \tilde{A} \cdot \tilde{B} = \left\{ \frac{\min(0.2,0.5)}{1} + \frac{\max[\min(0.2,1), \min(0.5,1)]}{2} + \frac{\max[\min(1,1), \min(0.7,0.5)]}{4} + \frac{\min(0.7,1)]}{8} \right\}$$

$$\tilde{V} = \tilde{A} \cdot \tilde{B} = \left\{ \frac{0.2}{1} + \frac{0.5}{2} + \frac{1}{4} + \frac{0.7]}{8} \right\}$$

Step 4. Defuzzification using centroid

The output from the previous step was the product between two fuzzy numbers which was the fuzzy weighted score $(\tilde{z})$. There were four possible combinations to obtain the fuzzy weighted scores as mentioned previously. The union of the all the possible calculated fuzzy weighted scores was the final fuzzy weighted scores for the criterion of concern:

$$\tilde{z} = \tilde{z}_1 \cup \tilde{z}_2 \cup \tilde{z}_3 \cup \tilde{z}_4 \qquad \textbf{5-31}$$

The centroid technique[22] was applied to $\tilde{z}_i = \tilde{w}_i \tilde{x}_i$ to obtained the defuzzified result for $\tilde{w}_i \tilde{x}_i$ (Eqn 5-33). The defuzzified result (z_i^*) was the crisp value representing the fuzzy weighted scores:

$$z_i^d = \frac{\sum \mu_{\tilde{z}}(z) \cdot z \, dz}{\sum \mu_{\tilde{z}}(z) dz} \qquad \textbf{5-32}$$

Each criterion had a defuzzified value (z_i^d) to represent its' weighted score. The defuzzified values for all the criteria were summed to obtained the overall aggregated value which was the global value for an alternative (Eqn 5-33).

$$v_{FSAW} = \sum_{i=1}^{n} z_i^d \qquad \textbf{5-33}$$

<u>Example</u>

A different example concerning the environmental criteria is used here from the technical criteria example used in Chapter 4. This is because the computation of the global values (aggregated scores) with fuzzy numbers is more complicated. For the purpose of illustration, a simpler example with fewer criteria is more appropriate. The

[22] Rationale for selection of centroid method is given in Section 2.8.1.2.

following demonstrates the procedure to obtain the calculated global values for the environmental category with two criteria: loss of high value ecosystem (c_4) and greenhouse gas emission (c_5). The following table presents the raw criteria scores and the criteria weights evaluated by the water user S20 (Table 5.11).

Table 5.11 Environmental criteria evaluated by water user S20

Environmental criteria	Mitigation value trade-off	Weights	Raw criteria scores (x_i^*)				
Strategy	$m_i	w_i	A	B	C	D	E
Loss of high value ecosystem (c_4)	45	0.45	0.44	0.68	0.68	0.76	0.78
Greenhouse gas (c_5)	55	0.55	0.67	0.18	0.37	0.47	0.74

Step 1. Determine the activated linguistic values for criteria weights and criteria scores

The following describes the procedure to determine the activated linguistic values for both the criteria weights and criteria scores for each criterion. Strategy A was taken as an example to illustrate the process.

Criteria weights – Loss of high value ecosystem (c_4)

The criterion 'loss of high value ecosystem' (c_4) was given a mitigation value trade-off $m_4 = 45$ by the water user S20, which was translated into a weight of $w_4 = 0.45$. According to Figure 4.10, two linguistic values 'unimportant' (UI) ($\tilde{a}_2$) and 'moderate important' (MI) ($\tilde{a}_3$) were activated by this input criteria weight. The activated fuzzy numbers are illustrated in Figure 5.5.

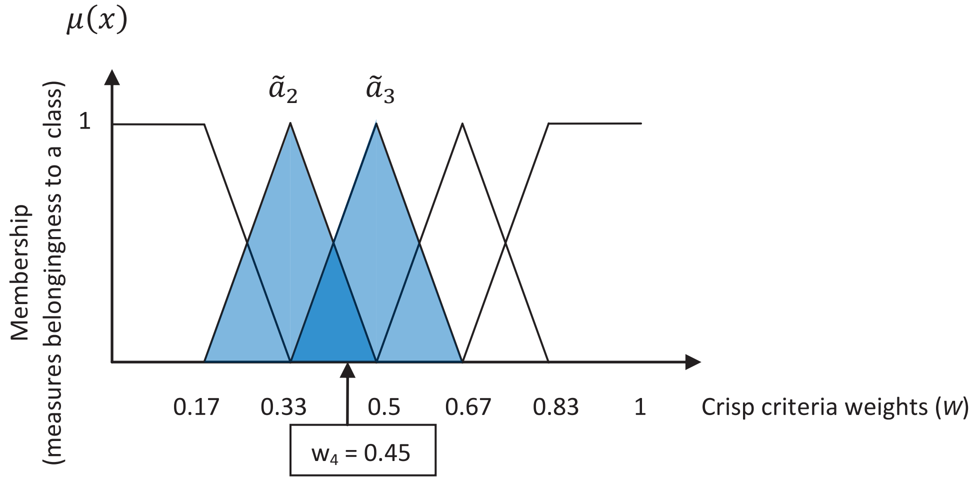


Figure 5.5 Activated fuzzy numbers by w_4 = 0.45 evaluated by water user S20 for Strategy A

Criteria weights – Greenhouse gas emissions (c5)

The criterion 'greenhouse gas emissions' (c_5) was given a mitigation value trade-off $m_4 = 55$ by the water user S20, which was translated into a weight of $w_5 = 0.55$. The activated linguistic values for this input criteria weight were 'moderately important' (MI) ($\tilde{a}_3$) and 'important' (I) ($\tilde{a}_4$) according to Figure 4.10. The activated fuzzy numbers are illustrated in Figure 5.6.

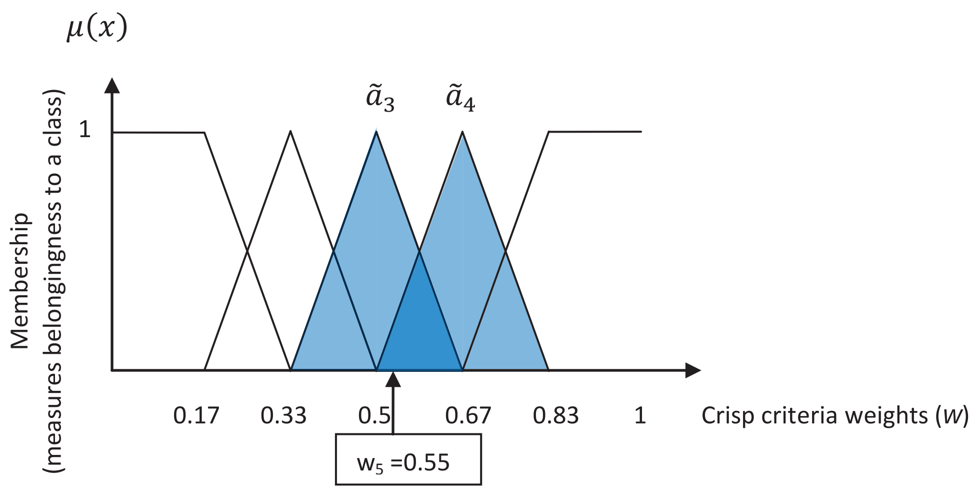


Figure 5.6 Activated fuzzy numbers by w_5 = 0.55 evaluated by water user S20 for Strategy A

Criteria scores – Loss of high value ecosystem (c4)

The mitigation level for the criterion 'loss of high value ecosystem' (c_4) was $m_4 = 45$ (Table 5.11). Based on Table 4.9, the mitigated normalising function MnF3 was applicable for the specified mitigation level ($m_4 = 45; MnF3: [42 \leq m_i \leq 59]$). Thus, MnF3 was applied to normalise the raw criteria scores for c_4. The raw criteria score for c_4 for Strategy A is $x_4^* = 0.44$ (Table 5.11). According to the MnF3 in Figure 4.11, two linguistic values were activated by the raw criteria score $x_4^* = 0.44$. They were 'low' in MnF3 (L3) $(\tilde{b}_{32})$ and 'medium' in MnF3 (M3) $(\tilde{b}_{33})$ (Figure 5.7).

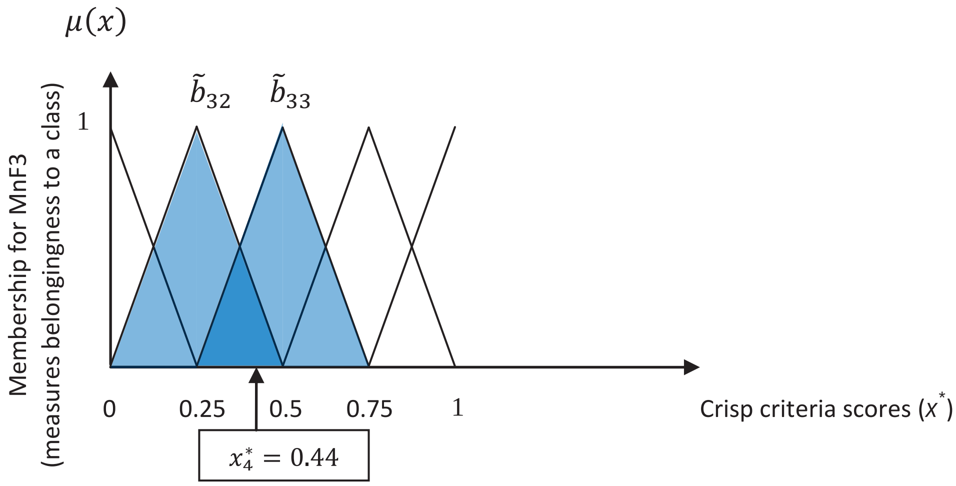


Figure 5.7 Activated fuzzy numbers by $x_4^* = 0.44$ evaluated by water user S20 for Strategy A

Criteria scores – Greenhouse gas emissions (c_5)

A similar procedure to the 'loss of high value ecosystem' was followed as for the 'greenhouse gas emission' (c_4) criterion. With the mitigation level at $m_5 = 55$ (Table 5.11), the mitigated normalising function MnF3 was applied according to Table 4.9 ($m_5 = 55; MnF3: [42 \leq m_i \leq 59]$). The raw criteria score for c_5 for Strategy A was $x_5^* = 0.67$ (Table 5.11). According to the MnF3 in Figure 4.11, two linguistic values were activated by the raw criteria score $x_5^* = 0.67$. They were 'medium' in MnF3 (M3) $(\tilde{b}_{33})$ and 'high' in MnF3 (H3) $(\tilde{b}_{34})$ (Figure 5.8).

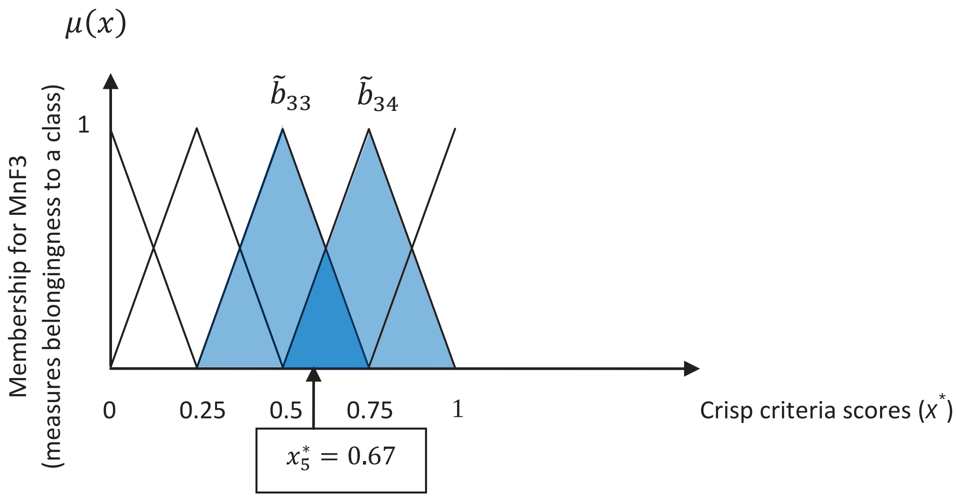


Figure 5.8 Activated fuzzy numbers by $x_5^* = 0.67$ evaluated by water user S20 for Strategy A

Step 2. Obtain the appropriate fuzzy scores and fuzzy weights

To obtain the appropriated linguistic values, the fuzzy numbers for the activated linguistic values were multiplied by the activated membership degrees. The following illustrates this process.

Criteria weights – Loss of high value ecosystem (c_4)

For c_4, the membership functions for the activated linguistic values 'unimportant' (UI) ($\tilde{a}_2$) and 'moderate important' (MI) ($\tilde{a}_3$) are presented in Eqn 4-11 and Eqn 4-12. The criteria weight for c_4 for Strategy A was $w_4 = 0.45$ (Table 5.11). The corresponding activated membership degrees were determined by substituting $w_4 = 0.45$ into Eqn 4-11 and Eqn 4-12 respectively as shown in the following:

$$\mu_{\tilde{a}_2}(0.45) = \frac{0.5 - 0.45}{0.17} = 0.29,$$

$$\mu_{\tilde{a}_3}(0.45) = \frac{0.45 - 0.33}{0.17} = 0.71.$$

The appropriated fuzzy number for the activated linguistic value UI ($\tilde{a}_{a2}$) was obtained by multiplying the activated membership degree, 0.29 by the activated fuzzy number ($\tilde{a}_2$):

$$\tilde{a}_{a2} = 0.29 \cdot \tilde{a}_2$$

Similarly, to obtain the appropriated fuzzy number for the linguistic value MI ($\tilde{a}_{a3}$), the activated membership degree 0.71 was multiplied to the fuzzy number ($\tilde{a}_3$):

$$\tilde{a}_{a3} = 0.71 \cdot \tilde{a}_3$$

The appropriated linguistic values UI and MI are illustrated in Figure 5.9.

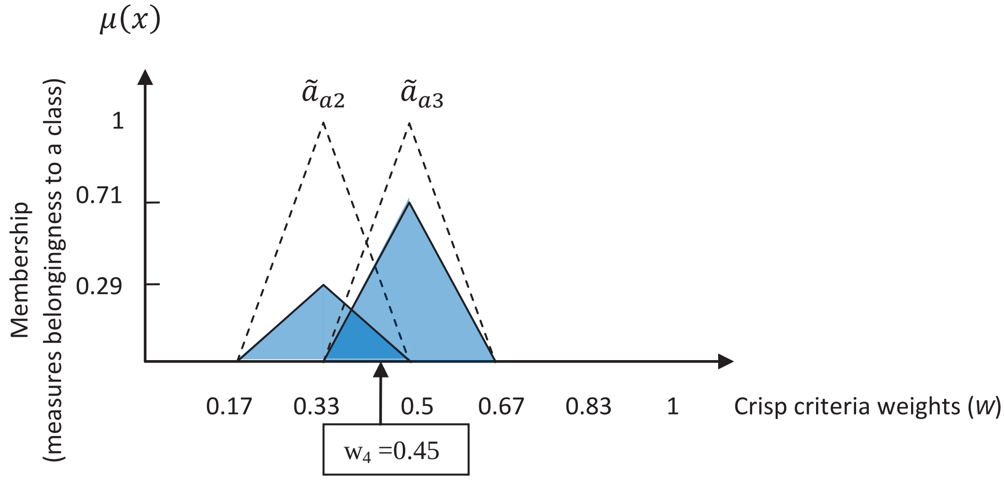


Figure 5.9 Appropriated fuzzy numbers by w_4 = 0.45 evaluated by water user S20 for Strategy A

Criteria weights – Greenhouse gas emissions (c_5)

For c_5, the membership functions for the activated linguistic values 'moderate important' (MI) ($\tilde{a}_3$) and 'important' (I) ($\tilde{a}_4$) are presented in Eqn 4-12 and Eqn 4-13. The criteria weight for c_5 for Strategy A was $w_5 = 0.55$ (Table 5.11). Using a similar procedure to the above, the corresponding activated membership degrees were:

$$\mu_{\tilde{a}_3}(0.55) = \frac{0.67 - 0.55}{0.67 - 0.5} = 0.71,$$

$$\mu_{\tilde{a}_4}(0.55) = \frac{0.55 - 0.5}{0.67 - 0.55} = 0.29.$$

The appropriated fuzzy numbers for the activated linguistic values MI ($\tilde{a}_{a3}$) and I ($\tilde{a}_{a4}$) are illustrated in Figure 5.10.

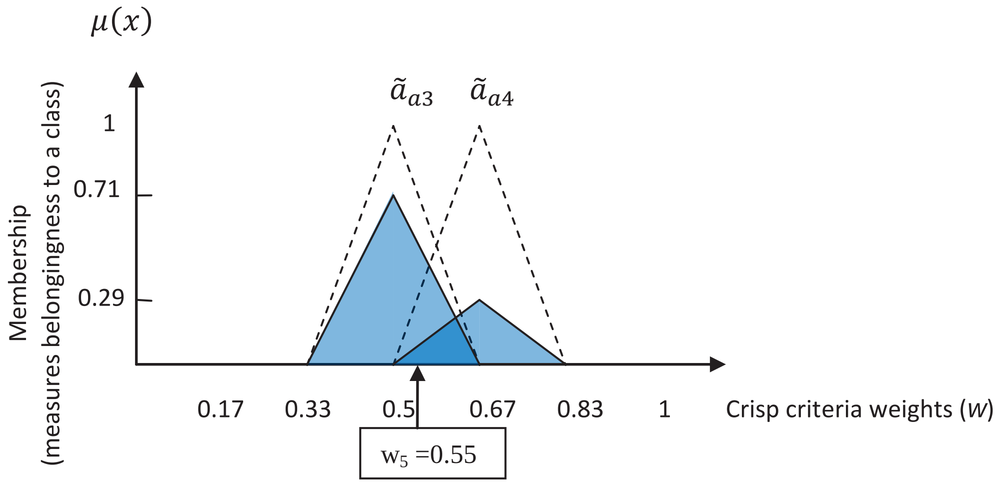


Figure 5.10 Appropriated fuzzy numbers by w_5 = 0.55 evaluated by water user S20 for Strategy A

Criteria scores – Loss of high value ecosystem (c_4)

The membership functions for the two activated linguistic values 'low' (L3) and 'medium' (M3) for MnF3 are presented in Eqn 5-34 and Eqn 5-35 in their long notation forms.

$$\mu_{\tilde{b}_{32}} = \begin{cases} 0 & x \leq 0 \\ \dfrac{x}{0.25} & 0 < x \leq 0.25 \\ \dfrac{0.5 - x}{0.25} & 0.25 < x \leq 0.5 \end{cases} \quad \text{5-34}$$

$$\mu_{\tilde{b}_{33}} = \begin{cases} 0 & x \leq 0.25 \\ \dfrac{x - 0.25}{0.25} & 0.25 < x \leq 0.50 \\ \dfrac{0.75 - x}{0.25} & 0.50 < x \leq 0.75 \\ 0 & x > 0.75 \end{cases} \quad \text{5-35}$$

The raw criteria score for Strategy A was $x_4^* = 0.44$ (Table 5.11). The corresponding activated membership degrees was determined by substituting $x_4^* = 0.44$ into Eqn 5-34 and Eqn 5-35 respectively as shown in the following:

$$\mu_{\tilde{b}_{32}}(0.44) = \frac{0.5 - 0.44}{0.25} = 0.24$$

$$\mu_{\tilde{b}_{33}}(0.44) = \frac{0.44 - 0.25}{0.25} = 0.76$$

The appropriated fuzzy numbers for the activated linguistic values 'low' $\left(\tilde{b}_{a32}\right)$ for MnF3 and 'medium' for MnF3 $\left(\tilde{b}_{a33}\right)$ are illustrated in Figure 5.11.

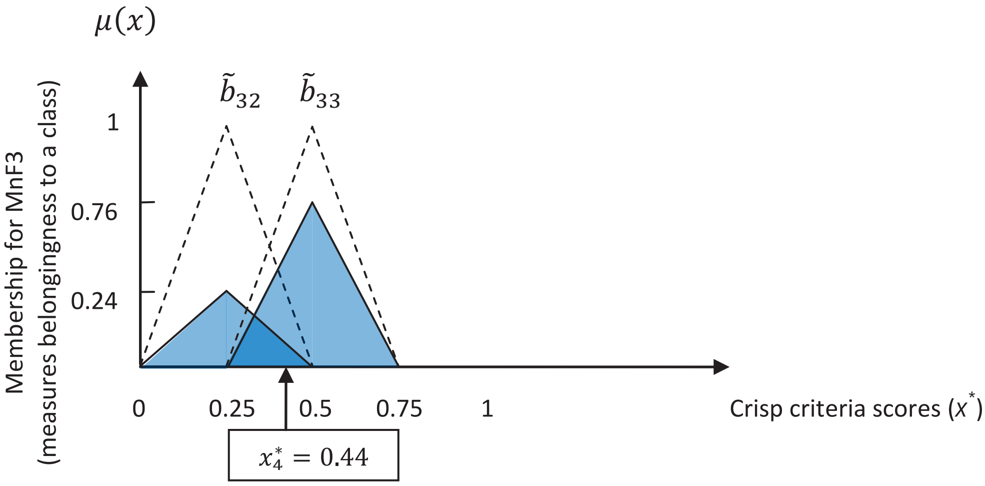


Figure 5.11 Activated fuzzy numbers by $x_4^* = 0.44$ evaluated by water users S20 for Strategy A

Criteria scores – Greenhouse gas emissions (c_5)

The membership functions for the activated two linguistic values 'medium' (M3) and 'high' (H3) for MnF3 are presented in Eqn 5-35 and Eqn 5-36 in their long notation forms.

$$\mu_{\tilde{b}_{34}} = \begin{cases} 0 & x \leq 0.5 \\ \dfrac{x - 0.5}{0.25} & 0.5 < x \leq 0.75 \\ \dfrac{1 - x}{0.25} & 0.75 < x \leq 1 \end{cases} \qquad \textbf{5-36}$$

The raw criteria score for strategy A was $x_5^* = 0.67$ (Table 5.11). The corresponding activated membership degrees were determined by substituting $x_5^* = 0.67$ into Eqn 5-35 and Eqn 5-36 respectively as shown in the following:

$$\mu_{\tilde{b}_{33}}(0.67) = \frac{0.75 - 0.67}{0.25} = 0.32,$$

$$\mu_{\tilde{b}_{34}}(0.67) = \frac{0.67 - 0.5}{0.25} = 0.68.$$

The appropriated fuzzy numbers for the activated linguistic values M3 $(\tilde{b}_{a33})$ and H3 $(\tilde{b}_{a34})$ are illustrated in Figure 5.12.

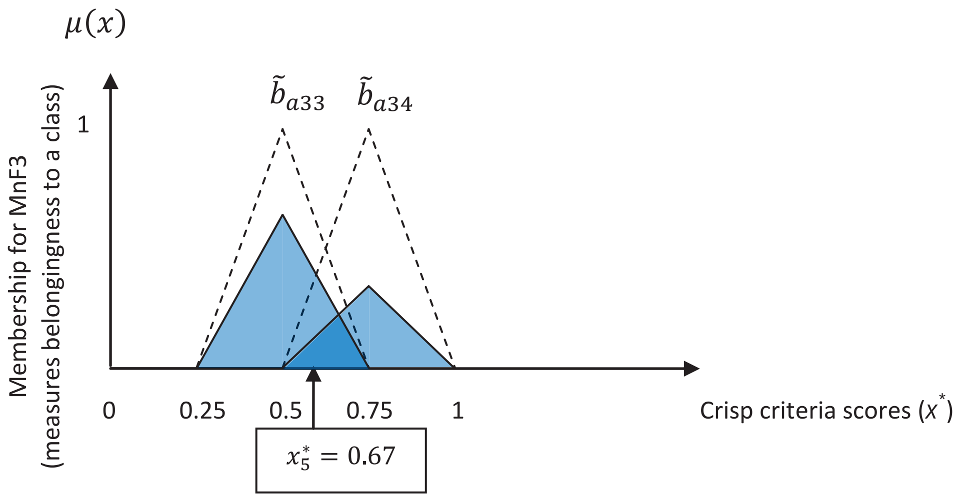


Figure 5.12 Activated fuzzy numbers by $x_5^* = 0.67$ evaluated by water users S20 for Strategy A

The membership functions for the appropriated fuzzy numbers $\tilde{a}_{a2}$, $\tilde{a}_{a3}$, $\tilde{b}_{a32}$, $\tilde{b}_{a33}$ are shown in Eqn 5-37 to 5-40.

$$\mu_{\tilde{a}_{a2}} = \begin{cases} 0 & x \leq 0.17 \\ 1.81(x - 0.17) & 0.17 < x \leq 0.33 \\ -1.7(x - 0.33) + 0.29 & 0.33 < x \leq 0.5 \\ 0 & x > 0.50 \end{cases} \quad \textbf{5-37}$$

$$\mu_{\tilde{a}_{a3}} = \begin{cases} 0 & x \leq 0.33 \\ 4.18(x - 0.33) & 0.33 < x \leq 0.5 \\ -4.18(x - 0.5) + 0.71 & 0.5 < x \leq 0.67 \\ 0 & x > 0.67 \end{cases} \quad \textbf{5-38}$$

$$\mu_{\tilde{b}_{a33}} = \begin{cases} 0.24x/0.25 & 0 < x \leq 0.25 \\ -0.96(x - 0.25) + 0.24 & 0.25 < x \leq 0.5 \\ 0 & x > 0.5 \end{cases} \quad \textbf{5-39}$$

$$\mu_{\tilde{b}_{a33}} = \begin{cases} 0 & x \leq 0.25 \\ 3.04(x - 0.25) & 0.25 < x \leq 0.50 \\ -3.04(x - 0.5) + 0.76 & 0.50 < x \leq 0.75 \\ 0 & x > 0.75 \end{cases} \quad \textbf{5-40}$$

Step 3. Obtain weighted scores $(\tilde{w}_i\tilde{x}_i)$

There were four possible combinations between $(\tilde{a}_s)$ and $(\tilde{b}_{tr})$. The following shows the four combinations using Eqn 5-25, 5-26, 5-27 and 5-28.

1	$\tilde{z}_1 = (0.29\tilde{a}_2 \cdot 0.24\tilde{b}_{32})$	e.g. Unimportant (UI) x Low from MnF3
2	$\tilde{z}_2 = (0.29\tilde{a}_2 \cdot 0.76\tilde{b}_{33})$	e.g. Unimportant (UI) x Medium from MnF3
3	$\tilde{z}_3 = (0.71\tilde{a}_3 \cdot 0.24\tilde{b}_{32})$	e.g. Moderate Important (MI) x Low from MnF3
4	$\tilde{z}_4 = (0.71\tilde{a}_2 \cdot 0.76\tilde{b}_{33})$	e.g. Moderate Important (MI) x Medium from MnF3

To obtain the fuzzy product between $(\tilde{a}_s)$ and $(\tilde{b}_{tr})$, Zadeh's extension principle was applied (Eqn 5-29), the product between (2) $0.29\tilde{a}_2 \cdot 0.76\tilde{b}_{33}$ was taken as an example. The interval for $\tilde{a}_2$ and $\tilde{b}_{33}$ were defined as I_1 and I_2 respectively:

$$I_1 = [0.17,0.5]$$

$$I_2 = [0.25,0.75]$$

Using Eqn 5-30, the interval of the product is as follows:

$$[0.17, 0.5] \times [0.25,0.75] = [min(0.04,0.13,0.13,0.38)\,, \max(0.04,0.13,0.13,0.38)]$$
$$= [0.04,0.38]$$

To illustrate the application of Zadeh's extension principle, $\tilde{a}_2$ and $\tilde{b}_{33}$ are expressed in short forms of notation (see Appendix D2).

$$\tilde{a}_{a_2} = \left\{\frac{0}{0.17} + \frac{0.0625}{0.18} + \frac{0.125}{0.19} + \cdots + \frac{1}{0.33} + \cdots + \frac{0.1176}{0.48} + \frac{0.0588}{0.49} + \frac{0}{0.50}\right\}$$

$$\tilde{x}_{b_{33}} = \left\{\frac{0}{0.25} + \frac{0.04}{0.26} + \frac{0.08}{0.27} + \cdots + \frac{1}{0.5} + \cdots + \frac{0.08}{0.73} + \frac{0.04}{0.74} + \frac{0}{0.75}\right\}$$

The appropriated $\tilde{a}_{a2}$ and $\tilde{b}_{a33}$ are:

$$\tilde{a}_{a2} = 0.29 \cdot \tilde{a}_2$$
$$= \left\{\frac{0}{0.17} + \frac{0.0181}{0.18} + \frac{0.0363}{0.19} + \cdots \frac{0.29}{0.33} + \cdots \frac{0.0341}{0.48} + \frac{0.0171}{0.49} + \frac{0}{0.50}\right\}$$

$$\tilde{b}_{a33} = 0.71 \cdot \tilde{b}_{33}$$
$$= \left\{\frac{0}{0.25} + \frac{0.0284}{0.26} + \frac{0.0568}{0.27} + \cdots + \frac{0.71}{0.5} + \cdots + \frac{0.0568}{0.73} + \frac{0.0284}{0.74} + \frac{0}{0.75}\right\}$$

Zadeh's extension principle was applied to the product $\tilde{a}_{a2} \cdot \tilde{b}_{a33}$ using Eqn 5-29 where the interval of the product is $[0.04,0.38]$. Derivation of this product was conducted using Matlab:

$$\tilde{z}_2 = \left\{\frac{0}{0.04} + \frac{0.0481}{0.05} + \frac{0.107}{0.06} + \cdots + \frac{0.52}{0.16} + \frac{0.52}{0.17} + \cdots + \frac{0.0332}{0.36} + \frac{0.011}{0.37} + \frac{0}{0.38}\right\}$$

Graphical presentation of the appropriated fuzzy criteria weights and appropriated fuzzy criteria scores for ‘loss of high value ecosystem’ and ‘greenhouse gas emissions’ are shown in Figure 5.13 and respectively. The four combinations between $(\tilde{a}_s)$ and $(\tilde{b}_{tr})$ are illustrated in Figure 5.14 using the appropriated fuzzy numbers from Figure 5.13.

Step 4: Defuzzification using centroid and aggregate

The union between the four products $\tilde{z}_1, \tilde{z}_2, \tilde{z}_3, \tilde{z}_4$ obtained from Step 3 was taken to give the overall fuzzy weighted score for the criterion ‘loss of high value ecosystem’ (c_4) using Eqn 5-31:

$$\tilde{z} = \tilde{z}_1 \cup \tilde{z}_2 \cup \tilde{z}_3 \cup \tilde{z}_4$$

$$\tilde{z} = \tilde{a}_{a2} \cdot \tilde{b}_{a32} \cup \tilde{a}_{a2} \cdot \tilde{b}_{a33} \cup \tilde{a}_{a3} \cdot \tilde{b}_{a32} \cup \tilde{a}_{a3} \cdot \tilde{b}_{a33}$$

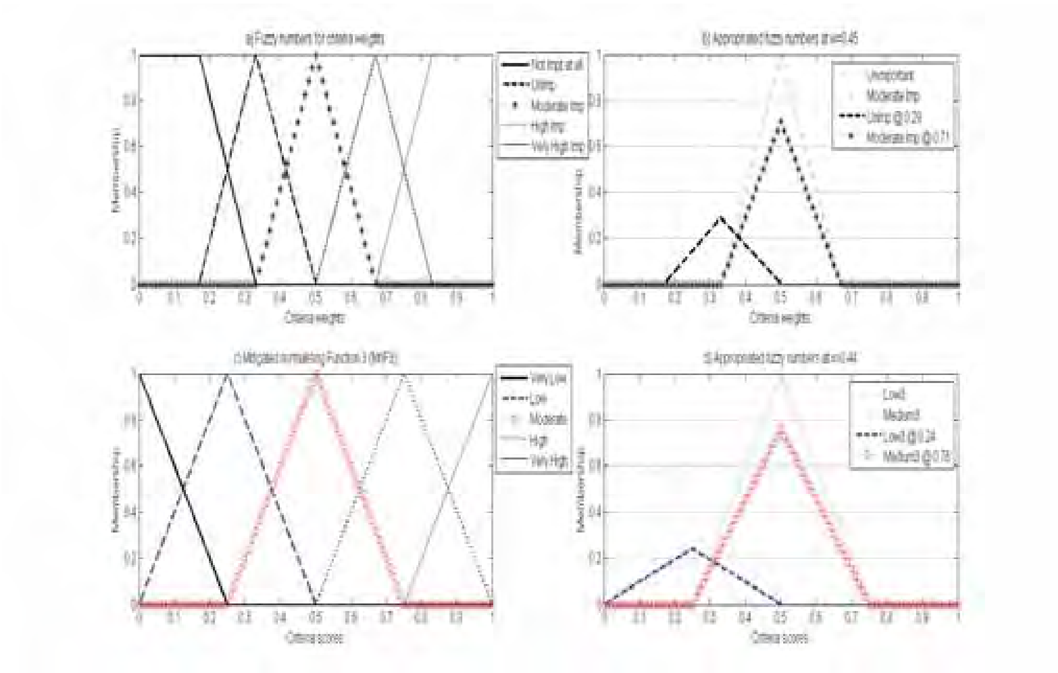


Figure 5.13 ‘Loss of high value ecosystem’ (c4) (a) fuzzy criteria weights (b) appropriated fuzzy criteria weights (c) fuzzy criteria scores (d) appropriated fuzzy criteria scores

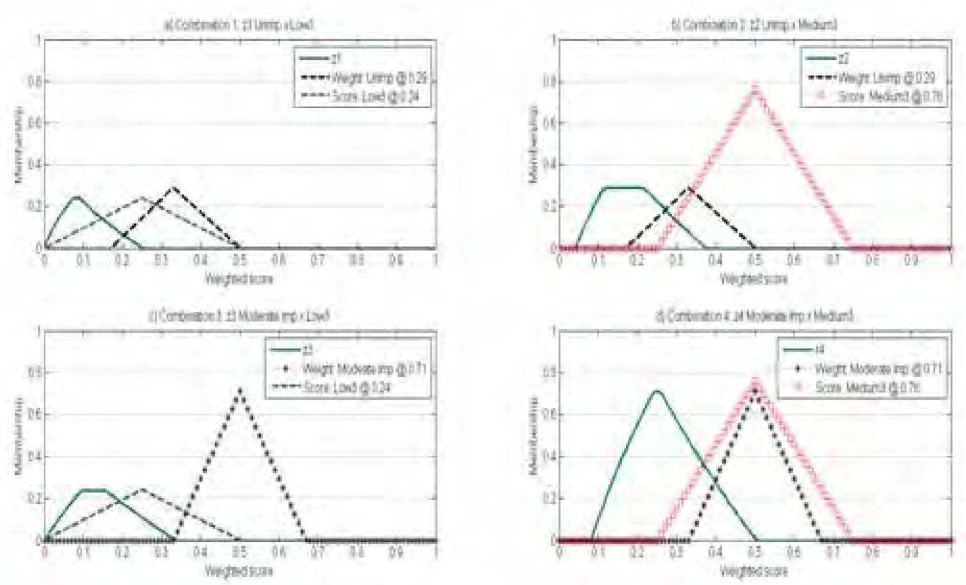


Figure 5.14 Example of modified FSAW Step 3: fuzzy weighted scores a) combination 1 b) combination 2 c) combination 3 and d) combination 4

Graphical representations of the procedure to obtain union between the four fuzzy weighted scores are shown in Figure 5.15. For a more thorough illustrate of step 1 to step 4,see Figure 5.17.

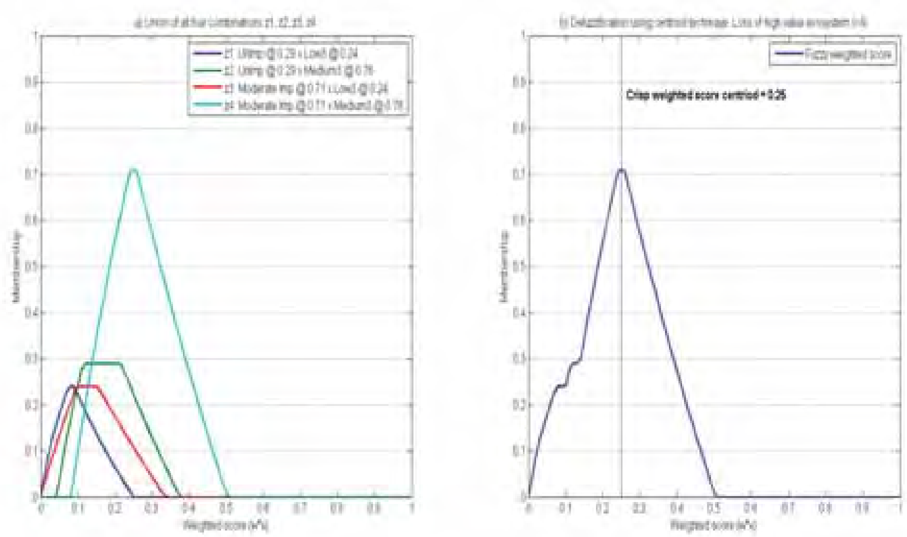


Figure 5.15 Fuzzy weighted scores for the (a) four combinations (b) final fuzzy weighted score (union of the four combinations)

The above procedure only illustrates the process of determining the weighted scores for 'loss of high value ecosystem' (c_4) for Strategy A (blue line in Figure 5.14 (b)). To obtain the global value for Strategy A, the fuzzy weighted score for the criterion 'greenhouse gas' was needed. The procedure to obtain the fuzzy weighted score for c_5 was similar to c_4 and therefore was omitted. The calculated fuzzy weighted scores for the two criteria were illustrated in Figure 5.16(a). The global values for Strategy A were obtained by adding the defuzzified fuzzy weighted scores z^d for c_4 and c_5 using Eqn 5-33:

$$z_4^d = \frac{\sum \mu_{\tilde{z}}(z) \cdot z \, dz}{\sum \mu_{\tilde{z}}(z) dz} = 0.25$$

$$z_5^d = \frac{\sum \mu_{\tilde{z}}(z) \cdot z \, dz}{\sum \mu_{\tilde{z}}(z) dz} = 0.41$$

$$z_A = (0.25 + 0.41) \times 100 = 66$$

The following figure shows the fuzzy weighted scores for strategies A, B, C, D and E.

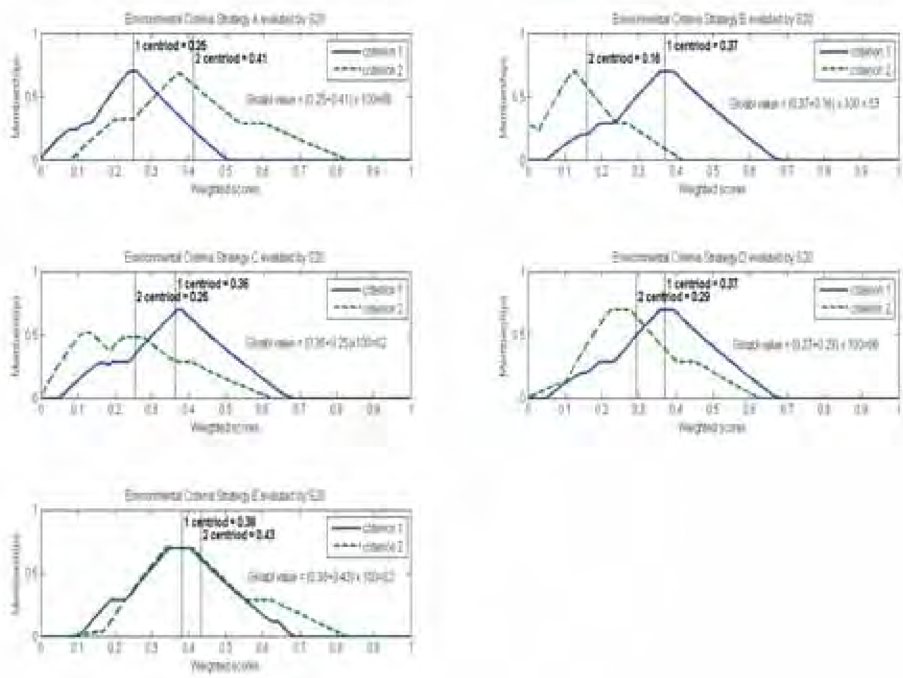


Figure 5.16 Fuzzy weighted scores for strategies (a) A, (b) B, (c) C, (d) D, (e) E

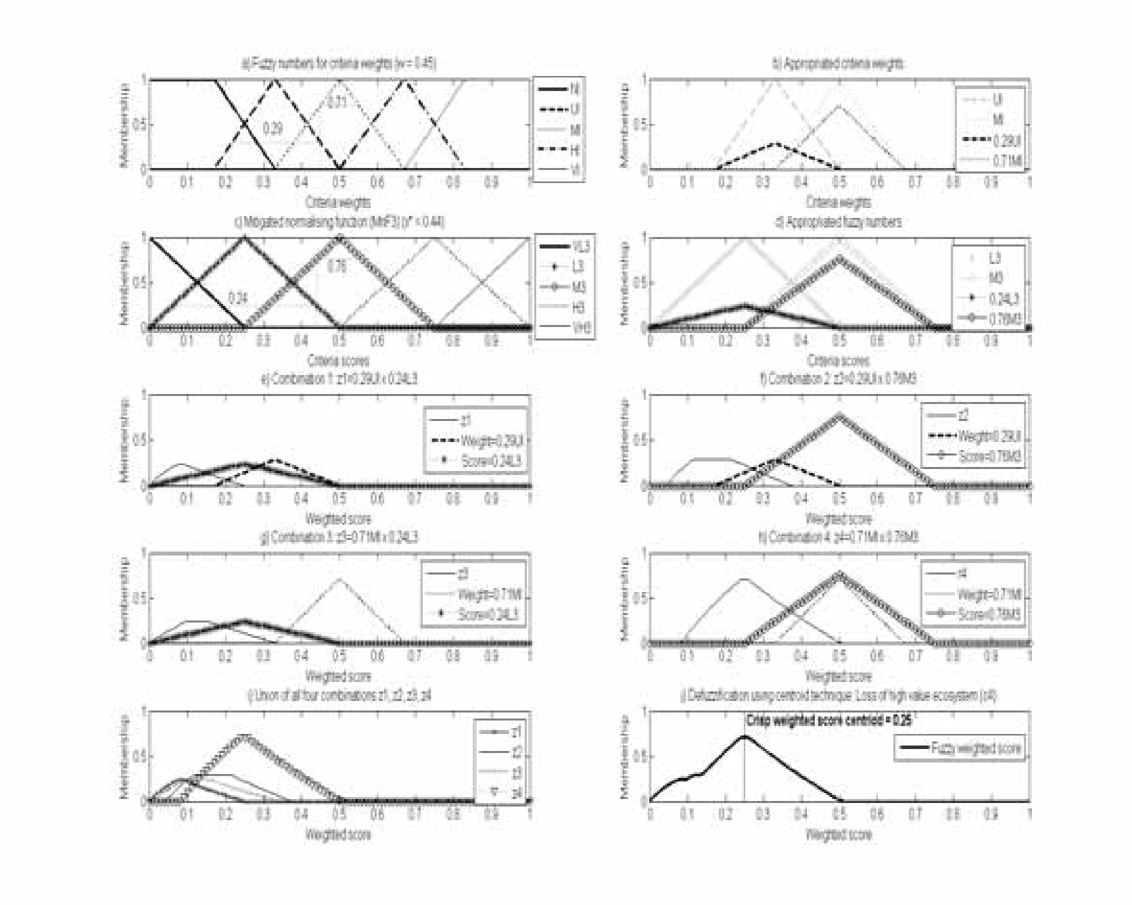


Figure 5.17 Case 2 example Step 1 to Step 4 for c4 'Loss of high value ecosystem'

Results

The results are presented in the format of scatterplots in Appendix F4. The scatterplots show the relationships between the observed global values by the participants and the calculated global values by the aggregation functions. The observed global values given by the participants can be found in Appendix F3.

5.3.3 Case 3. With criteria interaction

The following assumptions were made in Case 3:

- criteria were not assumed to be preferentially independent and thus the family of averaging aggregation could not be applied. Choquet integral was used instead as an aggregation tool to account for criteria interaction.
- judgement uncertainty was not considered and therefore crisp criteria scores and normalised crisp criteria scores were determined.

In Stage 2 Section 4.3.3, the task was concerned with obtaining two main inputs (criteria weights and criteria scores). Criteria weights in this case were described by the following two parameters which originated from the Choquet integral:

- Shapley index (ϕ_i)
- interaction index (I_{ij}).

For criteria scores, normalised crisp scores (x_i) were utilised because judgement uncertainty was not assumed for the derivation of normalised crisp value scores. In Stage 3, aggregation, the task was concerned with aggregating the criteria weights (in the form of Shapley index and interaction index) and criteria scores to obtain an output value (q) for each option. The output values (q) were used to establish preference order between alternatives. These three parameters (x, ϕ, I) were applied to the Choquet integral for aggregation. The Choquet integral aggregation model is shown in Eqn 5-41.

$$q = \sum_{i=1}^{n} \phi_i x_i - \frac{1}{2} \sum_{i=1}^{n} I_{ij} |x_i - x_j| \qquad \textbf{5-41}$$

Where: q is the aggregated score using the 2-additive Choquet integral

ϕ_i is the Shapley index for criterion *i*

x_i and x_j are the criteria scores for criterion *i* and *j*

I_{ij} is the interaction index between criterion *i* and *j*

Example

To illustrate the procedure, the same example from Stage 2 case 3 (Section 4.3.30 p.171) is used here. Four technical criteria (security of supply, reliability, flexibility and risks) from the GCWF case study were evaluated by the water manager M2. The determined Shapley and interaction indices were:

$$\phi_1 = 0.15, \phi_2 = 0.04, \phi_3 = 0.52, \phi_4 = 0.28$$

$$I_{12} = -0.04, I_{13} = 0.04, I_{14} = -0.13, I_{23} = 0.04, I_{24} = -0.09, I_{34} = 0.09, \alpha = 0.04$$

The normalised crisp criteria scores are presented in Table 5.12 (see Section 4.3.10(0) p.151 for derivation).

Table 5.12 Normalised crisp criteria scores

Technical raw scores	Normalised crisp criteria scores (x_i)				
Strategies	**A**	**B**	**C**	**D**	**E**
Security of supply (x_1)	0.38	0.34	0.34	0.50	0.56
Reliability (x_2)	0.58	0.76	0.64	0.62	0.72
Flexibility (x_3)	0.82	0.77	0.82	0.80	0.84
Risks (x_4)	0.78	0.85	0.85	0.82	0.76

The Choquet integral (q) can be determined according to Eqn 5-41:

$$q_{Strategy\ A} = 0.15x_1 + 0.04x_2 + 0.52x_3 + 0.28x_4 - 0.5(-0.04|x_1 - x_2| + 0.04|x_1 - x_3| - 0.13|x_1 - x_4| + 0.04|x_2 - x_3| - 0.09|x_2 - x_4| + 0.09|x_3 - x_4|)$$

From Table 5.12 Strategy A, the normalised criteria scores are:

$$x_1 = 0.38; x_2 = 0.58; x_3 = 0.82; x_4 = 0.78;$$

$$q_{Strategy\ A} = 0.15(0.38) + 0.04(0.58) + 0.52(0.82) + 0.28(0.78) - 0.5[-0.04|0.38 - 0.58| + 0.04|0.38 - 0.82| - 0.13|0.38 - 0.78| + 0.04|0.58 - 0.82| - 0.09|0.58 - 0.82| + 0.09|0.82 - 0.78|]$$

$$q_{Strategy\ A} = 75.17$$

$$q_{Strategy\ B} = 75.57$$

$$q_{Strategy\ C} = 77.83$$

$$q_{Strategy\ D} = 77.13$$

$$q_{Strategy} = 77.35$$

Results

The results are presented in the format of scatterplots. The scatterplots show the relationships between the observed global values by the participants and the calculated aggregated scores by the aggregation functions. They can be found in Appendix F4. The observed global values given by the participants can be found in Appendix F3. The preferences expressed by the DMs are presented in F5.

5.3.4 Case 4. With judgement uncertainty and criteria interaction

The following assumptions were made in this case:

- criteria were not assumed to be preferentially independent and thus the family of averaging aggregation could not be applied. The Choquet integral was used instead as an aggregation tool to account for criteria interaction. (Criteria interaction was explained in Section 2.5.4 p.54 and Appendix D2 details the Choquet integral.)
- judgement uncertainty was assumed and therefore fuzzy criteria weights and fuzzy criteria scores were determined.

The two inputs required for this case were:

- Shapley and interaction indices
- defuzzified criteria scores.

Shapley index and interaction index were both identified from Stage 2 preference elicitation and modelling under case 3 (Section 4.3.30 p. 167). For criteria scores, defuzzified criteria scores were used because judgement uncertainty was assumed. In this stage (3), the two inputs (Shapley and interaction indices) and defuzzified criteria scores were aggregated to obtain the overall value (q) for each option using Eqn 5-42.

$$q = \sum_{i=1}^{n} \phi_i x_i^d - \frac{1}{2}\sum_{i=1}^{n} I_{ij}\left|x_i^d - x_j^d\right| \qquad \textbf{5-42}$$

where

q is the aggregated score using the 2-additive Choquet integral

ϕ_i is the Shapley index for criterion *i*

x_i^d and x_j^d are the defuzzified criteria scores for criterion *i* and *j*

I_{ij} is the interaction index between criterion *i* and *j*.

Example

The defuzzified criteria weights according to the water manager M2's evaluation are presented in Table 5.13.

Table 5.13 Defuzzified criteria scores for technical criteria evaluated by water manager M2

Technical raw scores	Defuzzified criteria scores$(x_i^d \times 100)$				
Strategies	**A**	**B**	**C**	**D**	**E**
Security of supply (x_1)	38	33	33	50	55
Reliability (x_2)	57	75	64	62	73
Flexibility (x_3)	63	60	63	63	63
Risks (x_4)	62	63	63	63	60

Substituting the defuzzified criteria scores (x_i^d) from Table 5.13 and the Shapley/interaction indices from the previous example (Section 5.3.30 p.220) into Eqn 5-42, the Choquet integrals (q) for each of the strategies are as follows:

$$q_{Strategy\ A} = 0.15x_1^d + 0.04x_2^d + 0.52x_3^d + 0.28x_4^d - 0.5\big(-0.04\left|x_1^d - x_2^d\right| + 0.04\left|x_1^d - x_3^d\right| - 0.13\left|x_1^d - x_4^d\right| + 0.04\left|x_2^d - x_3^d\right| - 0.09\left|x_2^d - x_4^d\right| + 0.09\left|x_3^d - x_4^d\right|\big)$$

From Table 5.13 for Strategy A, the defuzzified criteria scores are:

$$x_1^d = 0.38; x_2^d = 0.57; x_3^d = 0.63; x_4^d = 0.62;$$

$$q_{Strategy\ A} = 0.15(0.38) + 0.04(0.58) + 0.52(0.82) + 0.28(0.78) - 0.5[-0.04|0.38 - 0.58| + 0.04|0.38 - 0.63| - 0.13|0.38 - 0.62| + 0.04|0.57 - 0.63| - 0.09|0.57 - 0.62| + 0.09|0.63 - 0.62|]$$

$$q_{Strategy\ A} = 60$$

$$q_{Strategy\ B} = 60$$

$$q_{Strategy\ C} = 61$$

$$q_{Strategy\ D} = 62$$

$$q_{Strategy\ E} = 62$$

The defuzzified criteria scores for all strategies are summarised in Table 5.14.

Table 5.14 Defuzzified criteria scores for technical criteria evaluated by water manager M2

Technical raw scores	Defuzzified criteria scores$(x_i^d \times 100)$				
Strategies	**A**	**B**	**C**	**D**	**E**
Observed global values (M2)	**70**	**50**	**90**	**80**	**60**
Weighted average (WA)	48	55	49	56	64
Average (AA)	64	68	66	68	72
Geometric Averages (GA)	61	64	62	67	71
Harmonic Averages (HA)	58	59	58	66	70
Median (MED)	68	76	73	71	74
Weighted Median (WMED)	49	53	50	53	57
Product Median (PMED)	43	51	48	46	49
Lukasiewicz Median (LMED)	49	53	50	53	56
OWA Quantifier (OWAqua)	62	65	64	67	70
OWA Orness (OWAorn)	68	72	71	72	74
OWA Entropy (OWAent)	64	68	66	68	72
OWA Optimistic (OWAopt)	68	70	70	72	74
OWA Pessimistic (OWAper)	66	69	68	70	73
Case 2 FSAW	78	84	80	85	93
Case 3 Choquet integral (CI)	75	76	78	77	77
Case 4 Fuzzy Choquet integral (FCI)	60	60	61	62	62

Results

The results are presented in the format of scatterplots. The scatterplots show the relationships between the observed global values by the participants and the calculated aggregated scores by the aggregation functions. They can be found in Appendix F4. The observed global values given by the participants can be found in Appendix F3. The preferences expressed by the DMs are presented in F5.

5.4 Correlation analysis

As a brief recap, Section 5.3 outlines the aggregation phase of the four preference models, and presents the calculated global values. In this section, the calculated global values are compared to the observed global values in the form of correlation analysis. The average observed global values are presented Figure 5.18. They are arranged by the criteria categories: social, ecosystem, environment, technical, and overall. The individual observed global values for each participant are presented in Appendix F3.

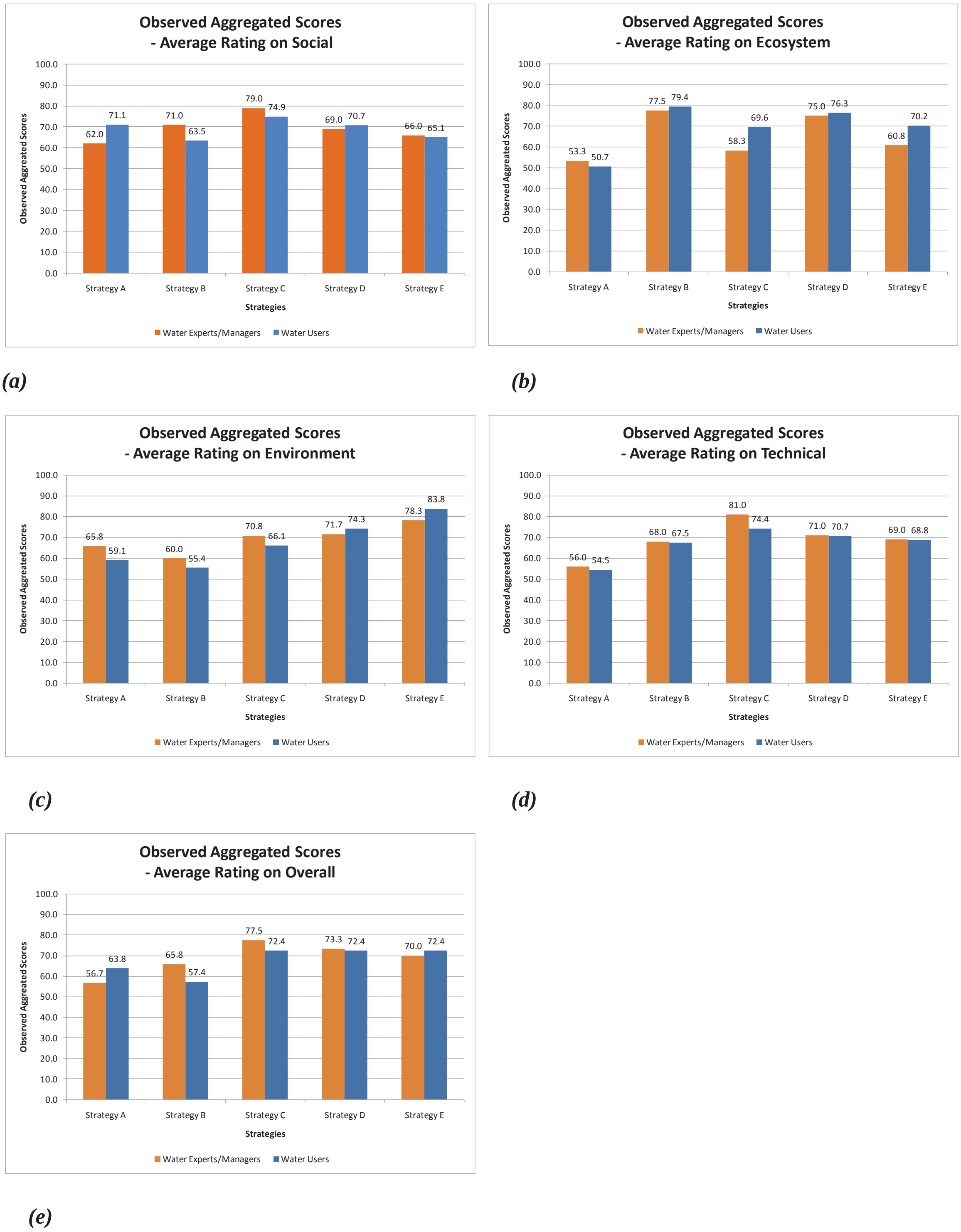


Figure 5.18 Average observed global values (a) social, (b) ecosystem, (c) environment, (d) technical, and (e) overall

The following table summarises the different aggregation functions that were used to determine the calculated global values (Table 5.15). The applied criteria categories for each case are also shown in the same table. Case 3 and Case 4 were only applied to the environment and technical categories because only these two criteria categories were assumed with criteria interaction.

Table 5.15 Summary of applications for the four cases

Case	Aggregation functions	Social (n=125)	Ecosystem (n=120)	Environment (n=130)	Technical (n=125)	Overall (n=125)
1	Averages, Median, Ordered Weighted Average (OWA)	✓	✓	✓	✓	✓
2	Fuzzy Simple Additive Weighting (FSAW)	✓	✓	✓	✓	✓
3	Choquet integral (CI)	-	✓	-	✓	-
4	Fuzzy Choquet integral (FCI)	-	✓	-	✓	-

Pearson's correlations (r) and Spearman's rank correlations (r_s) were determined between the calculated global values and the observed global values (Table 5.16 for Cases 1, 2, 3 and Table 5.17 for Case 4). Spearman's correlation is a non-parametric measure between the ranked global values whereas Pearson's correlation is a measure of the linear dependence of the two variables. Each participant evaluated 5 strategies per criterion category and there were 26 participants in total. A maximum sample size of 130 data set was available for each criterion category. However, some of the observed global values were not valid due to human error (i.e. missing values or inconsistencies). Therefore, the sample size for each criteria category was different as shown in Table 5.15.

Table 5.16 Correlations between observed global values and calculated global values that considered no criteria interaction

Correlation (n)	Average				Ordered Weighted Average					Median				Fuzzy
Social (125)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW
Pearson	0.222*	0.326**	0.132	0.108	0.311**	0.340**	0.295**	0.301**	0.275**	0.305**	0.197*	0.267**	0.203*	0.205*
Sig (2 tail)	0.013	0.000	0.142	0.230	0.000	0.000	0.001	0.001	0.002	0.001	0.028	0.003	0.023	0.022
Spearman	0.271**	0.359**	0.338**	0.315**	0.158	0.146	0.313**	0.344**	0.290**	0.368**	0.235**	0.283**	0.215*	0.194*
Sig (2 tail)	0.002	0.000	0.000	0.000	0.079	0.104	0.000	0.000	0.001	0.000	0.008	0.001	0.016	0.030
Ecosystem (120)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW
Pearson	0.544**	0.604**	0.599**	0.572**	0.614**	0.607**	0.603**	0.609**	0.599**	0.563**	0.562**	0.492**	0.573**	0.529**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Spearman	0.513**	0.598**	0.592**	0.592**	0.615**	0.614**	0.595**	0.603**	0.592**	0.585**	0.487**	0.403**	0.460**	0.442**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Environment (130)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn+	OWAqua	MED	WMED	LMED	PMED	FSAW
Pearson	0.463**	0.605**	0.602**	0.560**	0.584**	0.584**	0.605**	-	0.605**	0.605**	0.365**	0.572**	0.598**	0.636**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000
Spearman	0.461**	0.641**	0.638**	0.608**	0.601**	0.601**	0.641**	-	0.652**	0.641**	0.361**	0.623**	0.646**	0.628**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000
Technical (125)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW
Pearson	0.123	0.217*	0.176*	0.179*	0.188*	0.186*	0.191*	0.161	0.176*	0.148	0.200*	0.191*	0.188*	0.291**
Sig (2 tail)	0.152	0.015	0.050	0.045	0.036	0.037	0.033	0.073	0.050	0.099	0.026	0.033	0.036	0.001
Spearman	0.185*	0.208*	0.196*	0.184*	0.203*	0.195*	0.207*	0.174	0.196*	0.153	0.204*	0.216*	0.173	0.292**
Sig (2 tail)	0.038	0.020	0.029	0.040	0.023	0.029	0.021	0.053	0.029	0.089	0.022	0.016	0.053	0.001
Overall (125)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW
Pearson	-0.153	-0.026	-0.059	-0.082	-0.017	-0.030	-0.026	0.009	-0.039	0.105	-0.146	-0.005	-0.067	0.094
Sig (2 tail)	0.089	0.770	0.510	0.362	0.853	0.737	0.770	0.922	0.665	0.243	0.103	0.955	0.460	0.298
Spearman	0.121	0.099	0.108	0.131	0.065	0.062	0.099	0.068	0.115	0.126	0.082	0.107	0.151	0.241**
Sig (2 tail)	0.180	0.274	0.230	0.147	0.469	0.491	0.274	0.452	0.203	0.160	0.366	0.233	0.094	0.007

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
+. OWAorn is not applicable with criteria less than or equal to two
WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

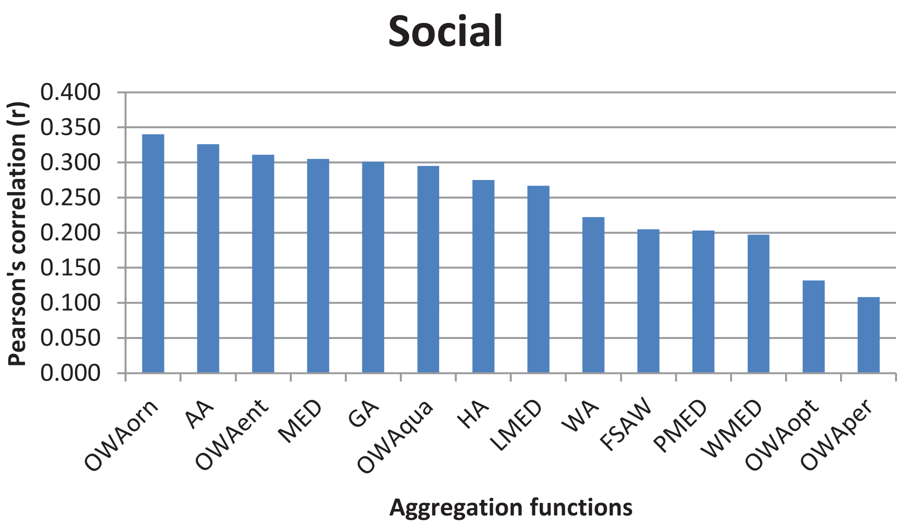
Table 5.17 Correlations between observed global values and calculated global values that considered criteria interaction

Correlation (n)	**Average**				**Ordered Weighted Average**					**Median**				**Fuzzy**	**Choquet Integral**	
Ecosystem (50)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW	CI	FCI
Pearson	0.492**	0.506**	0.500**	0.495**	0.520**	0.511**	0.504**	0.512**	0.500**	0.486**	0.461**	0.433**	0.482**	0.469**	0.479**	0.450**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.001	0.001	0.002
Spearman	0.475**	0.551**	0.539**	0.563**	0.564**	0.574**	0.540**	0.550**	0.539**	0.566**	0.404**	0.350*	0.343*	0.406**	0.411**	0.439**
Sig (2 tail)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.013	0.015	0.003	0.003	0.001
Technical (45)	WA	AA	GA	HA	OWAopt	OWAper	OWAent	OWAorn	OWAqua	MED	WMED	LMED	PMED	FSAW	CI	FCI
Pearson	-0.310*	0.136	0.164	0.094	0.199	0.172	0.175	0.181	0.164	0.062	0.194	0.144	0.336*	0.178	0.450**	0.425**
Sig (2 tail)	0.038	0.372	0.282	0.540	0.189	0.258	0.250	0.235	0.282	0.687	0.201	0.347	0.024	0.243	0.002	0.004
Spearman	-0.172	0.307*	0.210	0.261	0.192	0.168	0.179	0.139	0.210	0.249	0.316*	0.235	0.368*	0.104	0.376**	0.275*
Sig (2 tail)	0.258	0.040	0.166	0.083	0.207	0.271	0.238	0.364	0.166	0.099	0.035	0.121	0.013	0.495	0.000	0.011

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

5.4.1 Social

The aggregation functions that performed the best under social was O'Hagan's (1988) OWA orness approach (n = 125, r = 0.34, r_s = 0.34 $p < 0.01$), followed by arithmetic average (n = 125, r =0.33, r_s = 0.36, $p < 0.01$) (Table 5.16). In general, averages, median and OWA were better performing aggregation functions (Figure 5.19).



WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

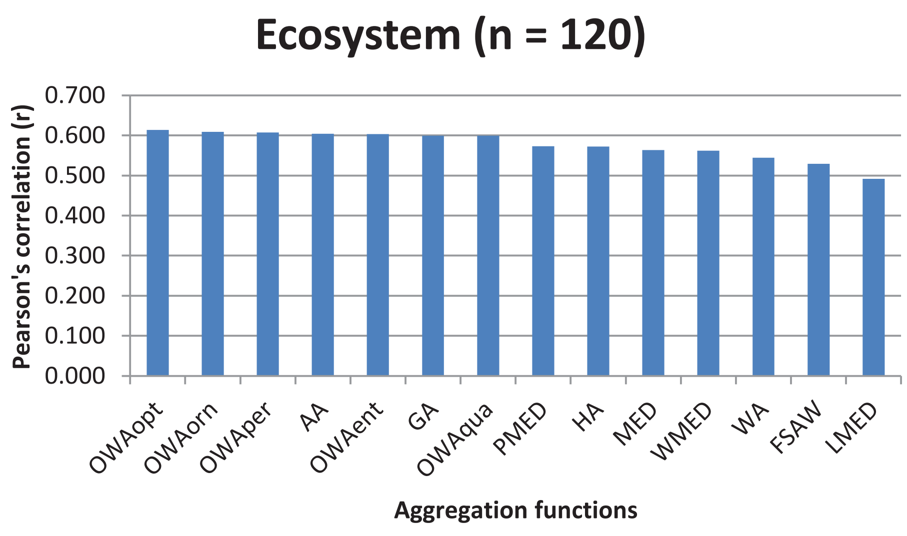
Figure 5.19 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for social

5.4.2 Ecosystem

The impact of dam raising included forest clearing, affecting significant floral and faunal species and further impeding the health of downstream waterways. The preferential independency condition was violated in this situation because there were interactions between these impacts. Choquet integral was applied to the ecosystem criteria to account for the interactions between the criteria. As explained previously, only the water experts and water managers were required to carry out the exercise with Choquet integral because it was more cognitively demanding to consider criteria interaction. The results for ecosystem are divided into two: (1) the water user group assuming there was no interaction between the criteria and (2) the water experts/managers group assuming there was interaction.

Water users - assume no interaction

The results for all aggregation operators demonstrated significant relationships with the observed global values, with all methods achieving $p < 0.01$. Generally all methods performed equally well for both Pearson and Spearman correlations with Filev and Yager's (1998) OWA approach performing the best ($n = 120$, $r = 0.61$, $p < 0.01$; $r_s = 0.62$, $p < 0.01$), followed by O'Hagan's (1988) OWA approach ($n = 120$, $r = 0.609$, $p < 0.01$; $r_s = 0.603$, $p < 0.01$) as shown in Table 5.16. The average functions generally performed better than FSAW (Figure 5.20).

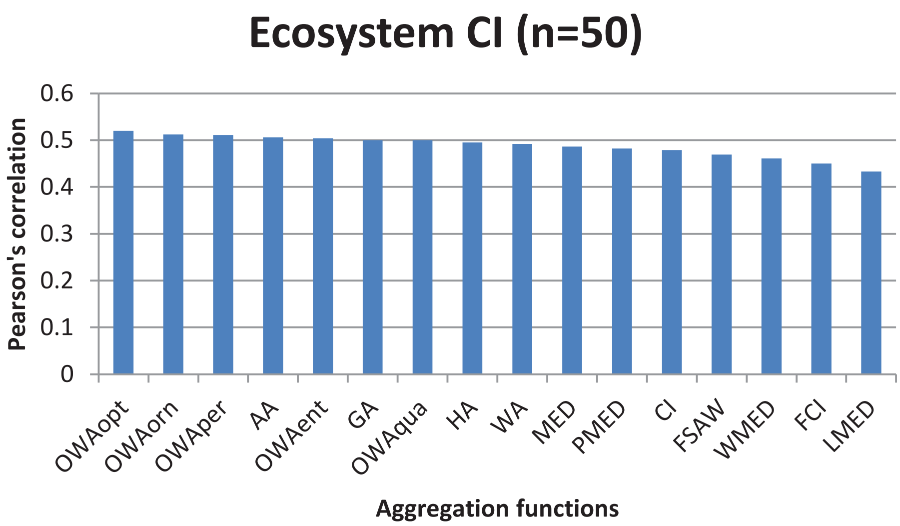


WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

Figure 5.20 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for ecosystem (water users)

Water experts and water managers – assume with interaction

The results for the water experts were similar to the water user group, in which the level of correlation between the observed and calculated global scores was generally high. Averaging and median operators appeared to be better performing aggregation functions. The level of correlation obtained for Choquet integral (CI) (n = 50, r = 0.48, p < 0.01; r_s = 0.41, p < 0.01) and fuzzy Choquet integral (FCI) (n = 50, r = 0.45, p < 0.05; r_s = 0.44, p < 0.01) were similar to other aggregation operators (Table 5.17, Figure 5.20).

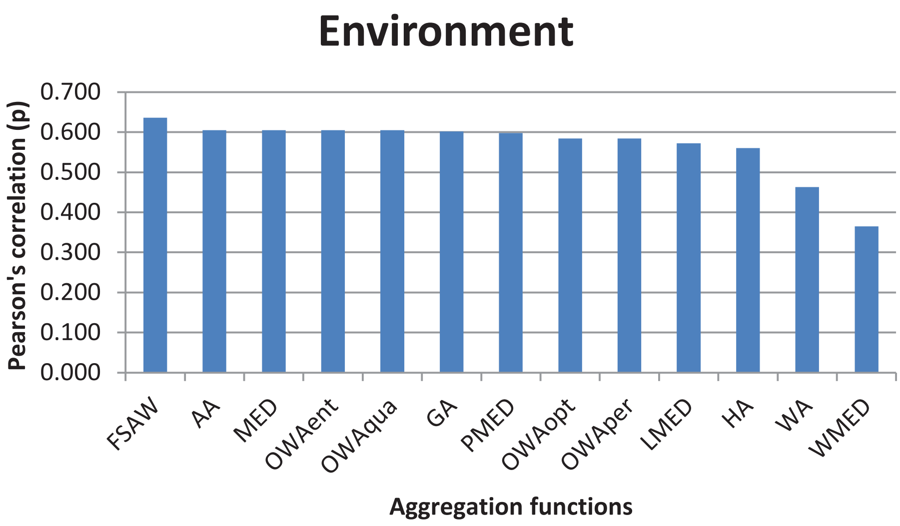


WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting; CI – Choquet Integral; FCI – fuzzy Choquet Integral

Figure 5.21 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for ecosystem (water managers/experts)

5.4.3 Environment

The level of correlations between the observed the calculated global values for the environmental criteria were the highest among all the other categories. FSAW was the best performing aggregation operator (n = 130, r = 0.64, p < 0.01; r_s = 0.63, p < 0.01), as shown in Table 5.16 and Figure 5.21. A possible reason for this shift was that as the participants became more familiar with the case study, they considered more factors and uncertainty became more important.



WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

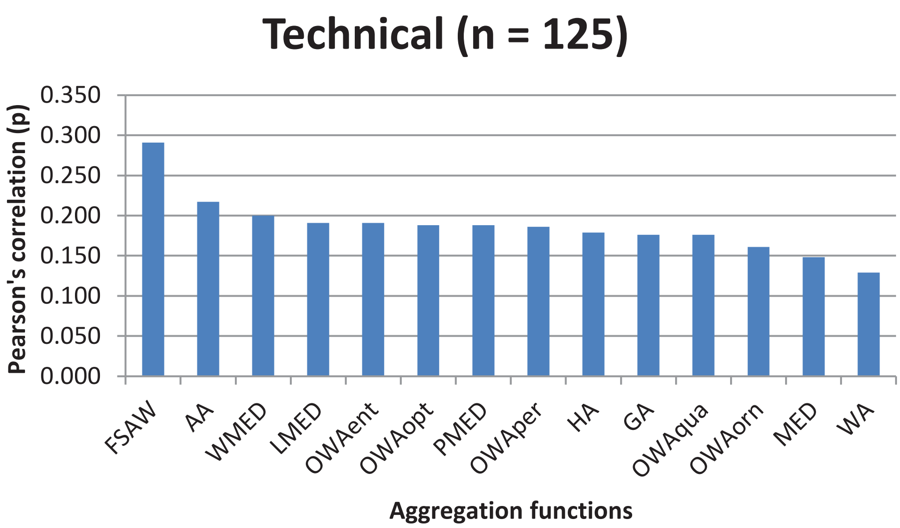
Figure 5.22 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for environment

5.4.4 Technical

Similar to the ecosystem criteria, interactions occurred between the technical criteria (security of supply, reliability, flexibility and risks). Only the water experts and water managers were required to carry out the exercise with Choquet integral because it was more cognitively demanding to consider criteria interaction. The results for technical are therefore divided into two parts: (1) the water user group assuming there was no interaction between the criteria and (2) the water experts/managers group assuming there was interaction.

Water users – assume no interaction

The level of correlation between the observed and calculated global values was generally low for the technical criteria. The only aggregation operator that had a significant correlation was FSAW (n = 125, r = 0.29, $p < 0.01$; r_s = 0.29, $p < 0.01$) (Table 5.16, Figure 5.22).

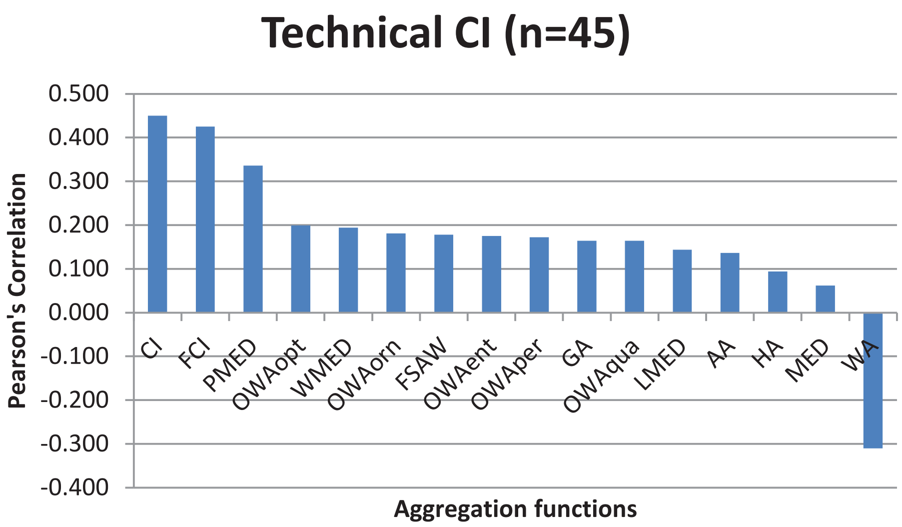


WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

Figure 5.23 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for technical

Water experts and managers – assume interaction

In the case which considered interaction, the Choquet integral (CI) (n = 45, r = 0.45, $p <$ 0.01; r_s = 0.49, $p < 0.01$) and fuzzy Choquet integral (FCI) (n = 45, r = 0.43, $p < 0.01$; r_s = 0.28, $p < 0.05$) outperformed all the other aggregation operators (Table 5.17, Figure 5.24). This showed that interaction played an important role in affecting the participants' judgement. This also showed the use of the Choquet integral was an appropriate approximation to the participants' aggregation if there were interactions between criteria in this case. In comparison to the ecosystem criteria, the influence of criteria interaction was not as obvious. A main reason for the difference was the level of criteria interaction between the ecosystem criteria was not as strong as the technical criteria. In the ecosystem section, only the clearance of forest and loss of significant fauna and flora had significant interactions. The level of interactions was also not so apparent to the participants because this required localised knowledge of the environment — the participants' expertise was generally stronger on the technical issues.

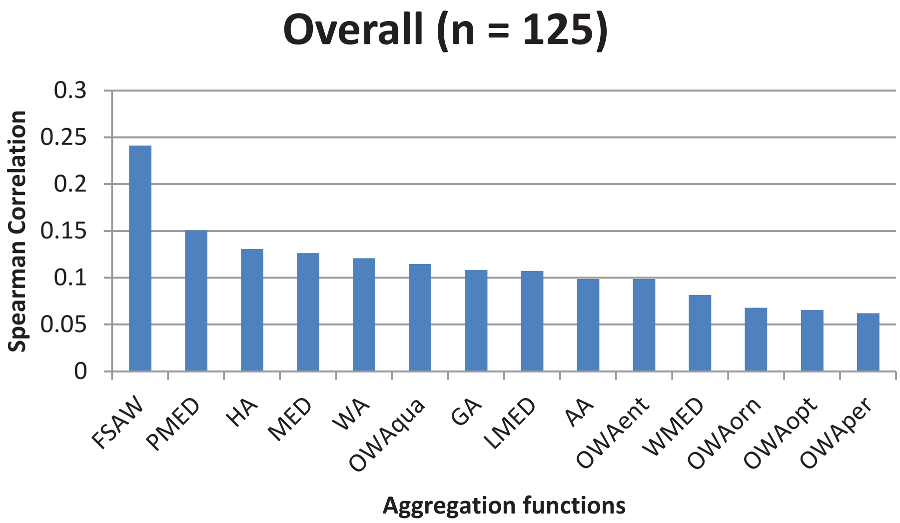


WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - FSAW Fuzzy Simple Additive Weighting; CI – Choquet Integral; FCI – Fuzzy Choquet Integral

Figure 5.24 Pearson's correlation (r) between observed global scores and calculated global scores using different aggregation functions for technical

5.4.5 Overall

The Pearson's correlation showed no significant relationships between the overall calculated global values and observed global values. The only aggregation operator that had a positive relationship with the observed global scores were Median (n = 125, r = 0.11, p > 0.05) and FSAW (n = 125, r = 0.09, p > 0.05). In terms of Spearman correlation, FSAW was the only aggregation function that had a significant relationship with the observed global values (n = 125, r_s = 0.24, $p < 0.05$) (Table 5.16, Figure 5.25). This is a good indication that the conventional aggregation techniques may not be appropriate in this situation given that there were multiple aspects and uncertainty played an important role in influencing the results.



WA – weighted average, AA – arithmetic average, GA – geometric average, HA – harmonic average, MED –median, WMED – weighted median, LMED – Lukasiewicz median, PMED – product median, OWAqua – ordered weighted average Yager's (1988) quantifier approach, OWAorn - O'Hagan's (1988) orness approach, OWAent - Fullér and Majlender's (2001) entropy approach, OWAopt - Filev and Yager's (1998) optimistic approach, OWApes - Filev and Yager's (1998) pessimistic approach, FSAW - Fuzzy Simple Additive Weighting

Figure 5.25 Spearman correlation (r) between observed global scores and calculated global scores using different aggregation functions for overall

5.4.6 Key results

Key points obtained from the correlation analyses are summarised as follows.

The level of understanding of the decision problem by the DMs directly affect their 'internal' mode of aggregation

Averaging function (OWA) outperformed all the other aggregation functions for the social and ecosystem categories (Table 5.18). However, this was different for the environment, technical and overall categories, which happened to be the last three exercises in the decision making process. FSAW was ranked either first or second for having the highest correlation with the observed global values (Table 5.18). FSAW, CI and FCI became better aggregation functions toward the later part of the process. One possible reason is that the participants were not familiar with the decision problem in the beginning of the exercise. The social and ecosystem section were the first two exercises in the workbook and it was likely that the participants did not have enough information at the time to consider other factors. Therefore, participants preferred the more direct aggregation methods in early phase of the process (i.e. ordered weighted average, arithmetic average and median).

As a general finding, the averaging function is useful as a first approach to model DMs' preferences for alternatives. However, during the course of the decision making process, as DMs become more familiar with the problems, they may require more information which may not be available. This situation is common and may lead to imprecise judgements because DMs cannot make trade-offs with full reconciliation of all possible factors. Therefore, averaging function is no longer an adequate aggregation model to represent DMs' true preferences in this situation. This is when the FSAW becomes useful. FSAW is able to model the impreciseness in human judgement under partially informed situations. As demonstrated in the case study, the outcomes from the FSAW analyses reflected more closely the DMs' real preference (observed global values) toward the later part of the interviews (i.e. environmental, technical and overall criteria categories). The influence of uncertainty became more apparent as the participants were more familiar with the decision making problem. They asked more questions and required more information. Some of the information was not available immediately during the interview process, therefore the participants were forced to make rough trade-off judgements.

Ordered weighted average (OWA) is a suitable surrogate for weighted average if no uncertainty is involved.

Amongst the averaging functions (classical averages, median and ordered weighted averages) ordered weighted averages was found to outperform the other averaging functions in this research.

DMs' understanding of the interaction between criteria directly affects the usefulness of Choquet integral (CI)

There were only two criteria categories (*ecosystem* and *technical*) which involved criteria interaction in the case study assessment. In the first criteria category (*ecosystem*), all three methods averages (or specifically weighted average), FSAW and CI performed equally well to model the observed global values. In the second category (*technical*), the Choquet integral outperformed all the other aggregation functions in modelling DMs' observed global values. The main reason for this is that the majority of the participants were engineers. They were more familiar with the technical aspects of urban water systems, and therefore, they could understand better the interaction between the technical criteria. This was directly reflected in the improved ranking of Choquet integral in the technical category. On the other hand, the participants were not familiar with the issues associated with the ecological system. This shows that the participants' understanding of the criteria interaction directly affects the usefulness of Choquet integral.

Table 5.18 Summary of correlation results for Case 1 and Case 2

	Case 1		Case 2	
	Ranking of Averaging function[23] (Pearson's correlation)	Ranking of Averaging function (Spearman's correlation)	Ranking of FSAW (Pearson's correlation)	Ranking of FSAW (Spearman's correlation)
Social	1st (OWAorn)	1st (MED)	10th	12th
Ecosystem	1st (OWAopt)	1st (OWAopt)	13th	13th
Environment	2nd (AA)	1st (OWAqua)	1st	7th
Technical	2nd (AA)	2nd (LMED)	1st	1st
Overall	1st (MED)	2nd (PMED)	2nd	1st

Table 5.19 Summary of correlation results for Case 3 and Case 4

	Case 3		Case 4	
	Ranking of CI (Pearson's correlation)	Ranking of CI (Spearman's correlation)	Ranking of FCI (Pearson's correlation)	Ranking of FCI (Spearman's correlation)
Ecosystem	12th	12th	15th	11th
Technical	1st	1st	2nd	5th

5.5 Sensitivity analysis

The output of a decision support methodology is critically related to the input data. It is therefore of interest to explore the relationships between changes in the input values and subsequent output values from the model. Sensitivity analysis is the analytical procedure to examine these relationships that underpin the dynamic of the decision models. It examines the stability of the preferred alternative under changes to the key input parameters and investigates the need for more precise estimate of the input parameters (Insua and French, 1991).

Conventional sensitivity analysis for multi-criteria decision problems is concerned with changes to the criteria weights and criteria scores and their influences on the ranking of alternatives. This type of approach determines the minimum changes in the criteria weights and criteria scores that can alter the current optimal alternative ranking. These types of sensitivity analysis methods can be found in Bana e Costa (1988), French (1992), Triantaphyyllou and Sanchez (1997).

[23] Averging aggregation function include all aggregation operators under the classical averages (WA, AA, HA and GA), median (MED, WMED, LMED, PMED), and OWA (OWAqua, OWAorn, OWAent, OWAopt, OWApes). See Section 5.2.1 p.194 for their long notation.

Although it is of interest to understand the sensitivity of the output's alternative ranking to the changes in criteria weights and criteria scores, the significance of reporting them is to verify the assumptions made to describe the criteria weights and criteria scores. The purpose of conducting sensitivity analysis in this research is to identify which assumptions are appropriate candidates for additional investigation to further improve the model. An auxiliary purpose is to investigate the robustness of the decision model with variations to the key parameters. The following lists the assumptions made to describe the criteria weights and criteria scores for each of the four preference models (Table 5.20).

Table 5.20 Assumptions made to describe the criteria weights and criteria scores for the four cases

Case	Details	Assumptions
1	Without judgement uncertainty and criteria interaction	Criteria weights and criteria scores were described deterministically.
2	With judgement uncertainty	Criteria weights and criteria scores were described as fuzzy numbers. The shape of fuzzy numbers were assumed to be triangular or trapezoidal. The membership functions of the fuzzy numbers were pre-determined. Appropriated fuzzy numbers were more accurate approximations of DMs' preferences.
3	With criteria interaction	The Shapley index and interaction index represented the criteria weights and they were derived deterministically. The criteria scores were assumed to be deterministic.
4	With judgement uncertainty and criteria interaction	The Shapley index and interaction index represented the criteria weights and they were derived deterministically. The criteria scores were described by fuzzy numbers.

5.5.1 Case 1. Without judgement uncertainty and criteria interaction

The preference under this case was deterministic in that the criteria weights and criteria scores were treated as deterministic without uncertainty involved. No sensitivity analysis was conducted for this preference model because this had no implications on addressing the research questions. A number of sensitivity analysis methods on deterministic decision models have been developed (Insua and French, 1991; Triantaphyyllou and Sanchez, 1997; Proll *et al.*, 2001). They all share the common approach of identifying the smallest changes in the input parameters for altering the initial ranking of alternatives (Hyde, 2006). Triantaphyyllou and Sanchez (1997) concluded that the most sensitive decision criteria is the one with the highest weight and the choice of the MCDA method or number of alternative has little influence on the sensitivity results.

5.5.2 Case 2. With judgement uncertainty

The criteria weights and criteria scores were described as fuzzy numbers in this preference model. Four different scenarios were investigated in response to the assumptions made for this case in Table 5.20:

- Scenario 1. The shape of the fuzzy numbers for criteria weights were assumed to be Gaussian or in z-shaped (Figure 5.26)
- Scenario 2a. The membership functions of the fuzzy numbers for criteria weights were modified (Figure 5.27)
- Scenario 2b. The membership functions of the fuzzy numbers for criteria weights were modified again (Figure 5.28)
- Scenario 3. Fuzzy numbers were not appropriated (Bonissone's approach) (Figure 4.10).

Notice that only the criteria weights were modified in the first three scenarios, in order to observe the differences with the smallest change. The criteria weights and criteria scores remained unchanged in the last scenario, which in essence was the Bonissone's approach (see Appendix D1.2 for Bonissone's approach and Section 4.3.2 p.153 for the modified approach). These four scenarios were only applied to three categories including social, technical and overall criteria. The correlations between the analysed global values for the four scenarios and the observed global values are presented in Table 5.21.

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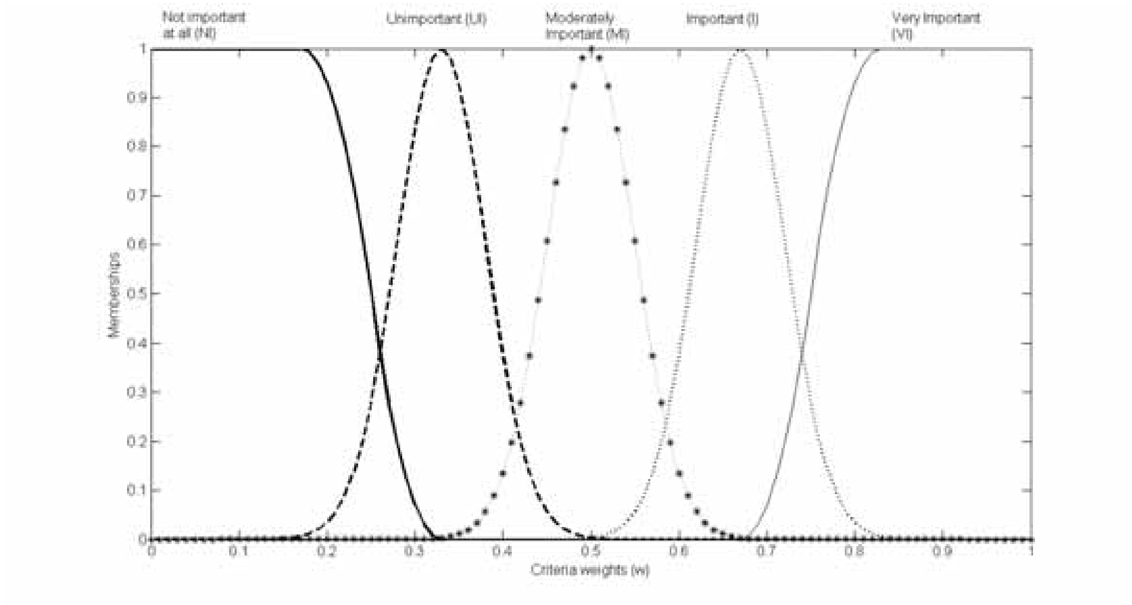


Figure 5.26 Fuzzy criteria weights for sensitive analysis scenario 1

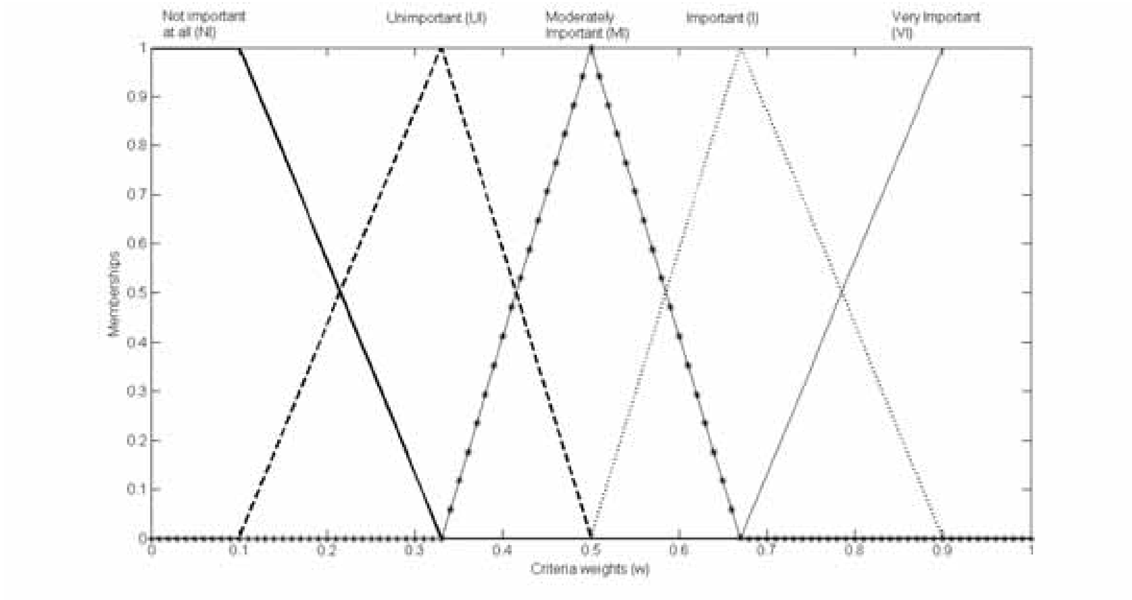


Figure 5.27 Fuzzy criteria weights for sensitive analysis scenario 2a

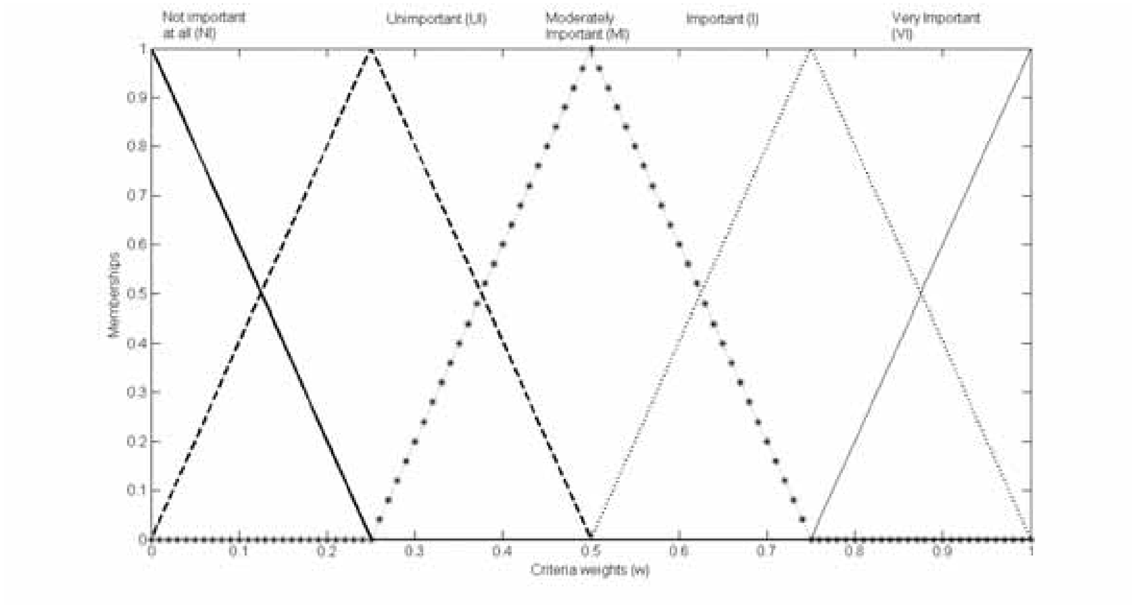


Figure 5.28 Fuzzy criteria weights for sensitive analysis scenario 2b

Table 5.21 Correlations between observed and calculated global values for Case 2 sensitivity analysis

		FSAW (Case 2)	Scenario 1	Scenario 2a	Scenario 2b	Scenario 3
Social	Pearson Correlation	0.205*	0.223*	0.301**	0.284**	0.203*
	Sig. (2-tailed)	0.022	0.012	0.001	0.001	0.023
	N	125	125	125	125	125
Technical	Pearson Correlation	0.291**	0.324**	0.266**	0.229*	0.334**
	Sig. (2-tailed)	0.001	0.000	0.003	0.010	0.000
	N	125	125	125	125	125
Overall	Pearson Correlation	0.094	0.108	0.101	0.043	0.079
	Sig. (2-tailed)	0.298	0.229	0.264	0.636	0.381
	N	125	125	125	125	125

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The correlations between the observed and calculated FSAW global values for case 2 are shown in column 3 of Table 5.21. The correlations for the four scenarios are compared to the FSAW correlations. The differences are not dramatic as expected. This suggests that modification of the criteria weights shape (scenario 1) and ranges (scenario 2a and 2b) are useful to 'fine-tune' the membership functions of the fuzzy numbers in order to model the observe preference better. The differences between Bonissone's approach (scenario 3) and the appropriated FSAW (a modification of Bonissone's approach – scenario 1) are not significant in all three cases. The main reason is that the centroid fuzzy ranking method employed in both methods only takes the geometric centre of the fuzzy number (see Appendix D1.3). The geometrical centres for both the original fuzzy number (in Bonissone's approach) and the appropriated fuzzy numbers (in the modified FSAW) are almost equal. Therefore the outputs from the two methods are not significantly different. Other types of fuzzy ranking methods (see Appendix D1.3) can be applied to take advantage of the appropriated fuzzy number in the modified Bonissone's approach.

5.5.3 Case 3. With criteria interaction

The Choquet integral was the aggregation function chosen for this preference model. Therefore, the criteria weights were described by Shapley index and interaction index. As discussed in Section 4.3.30 p.167, the strength of preference was the key input from the DMs to determine the Shapley index and the interaction index. In response to the assumption listed in Table 5.20 for this case, the strength of preference was modified in four scenarios as follows:

- Scenario 1. A different set of strength of preferences was derived by subtracting 1 from the strength of preference value
- Scenario 2. A different set of strength of preferences was derived by adding 1 to the initial strength of preference value
- Scenario 3. A different set of strength of preferences was derived by subtracting 2 from the strength of preference value
- Scenario 4. A different set of strength of preferences was derived by adding 2 to the initial strength of preference value.

These two modifications were only applied to ecosystem and technical which involved interacting criteria. The correlations between the observed and calculated global values for the four sensitivity analyses are shown in Table 5.22. The correlations for Case 3 and Case 4 are presented in the same table in column three and column four respectively. The correlations for the sensitivity analyses are compared to Case 3 and Case 4's correlations.

Table 5.22 Correlations between observed and calculated global values for Case 3 and Case 4 sensitivity analysis

		Case 3	Case 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ecosystem	Pearson	0.479**	0.456**	0.489**	0.484**	0.476**	0.483**
(n=50)	Sig. (2-tailed)	0.000	0.001	0.000	0.000	0.000	0.000
Technical	Pearson	0.450**	0.425**	0.376*	0.393**	0.272	0.243
(n=45)	Sig. (2-tailed)	0.002	0.004	0.011	0.008	0.070	0.108

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

The changes are not apparent in the ecosystem category but there is an apparent drop in the correlations for the technical category. As discussed earlier, the participants might not be so familiar with the criteria interaction between the ecology services. Therefore, there were no apparent changes for the ecosystem category. For the technical category, as the strengths of preference deviate from the original figures, the correlations between the observed and calculated global values dropped. This suggests that the analysed global values are sensitivity to the strength of preference.

5.5.4 Case 4. With judgement uncertainty and criteria interaction

The insights obtained from varying the key parameters in Case 2 and Case 3 were also applicable to the fuzzy Choquet integral method.

5.6 Conclusions

This chapter illustrates the use of aggregation, Stage 3 of the decision support approach. The aggregation stage generated the global values for the four preference models. Various forms of aggregation functions were applied to calculate the global values for the four cases. The calculated global values were compared to the observed global values in the form of correlation analyses. Three key points were obtained from the correlation analyses and they are summarised as follows.

The level of understanding of the decision problem by the DMs directly affects their 'internal' mode of aggregation

It was found that the correlation using Case 2 (fuzzy simple additive weighting) preference models improved as the DMs became more familiar with the decision problems. This suggests that judgement uncertainty plays a more important role as DMs consider a wider range of issues, their judgement became less precise as the decision making process unfolds.

Ordered weighted average is a suitable surrogate for weighted average if no uncertainty is involved

OWA consistently ranked among the top in the correlations analyses.

DMs' understanding of the interaction between criteria directly affects the usefulness of Choquet integral

CI outperformed all the other aggregation functions in the technical category, which happened to be the home discipline for a majority of the participants.

The sensitivity analysis for Case 2 and Case 3 showed that

- The calculated global values using FSAW is not very sensitive to minor changes to the shape or the range of fuzzy number. Changes to the shape or range of the fuzzy number are useful to 'fine-tune' the membership functions of the fuzzy numbers in order to model the observe preference better.
- The calculated global values using CI is sensitive to the strength of preference which depends on the DM's level of uncertainty of the criteria interaction.

6 Discussion and Conclusion

6.1 Introduction

This chapter outlines the points of discussion and draws conclusions for this thesis. In Section 6.2, the main findings of the research are tied back to the literature to highlight the gaps filled by this research. In Section 6.3 the main findings of the study are summarised. The outcome of the thesis, research limitations, and areas for future research are detailed in Sections 6.4, 6.5 and 6.6 respectively.

6.2 Discussion

For the purpose of highlighting new ideas that emerge as part of this thesis, a brief recap of the current practices in the discipline of urban water management is given and the gaps identified from the literature review in Chapter 2 are restated. Lastly, the results of this work are compared to the current theories and practices to identify findings of this thesis.

6.2.1 Literature review and key findings

A key finding from Chapter 2 (literature review) pertaining to the current development of MCDA in urban water management is summarised below to show how this research can inform the current debates.

- ***There is a great potential for MCDA as a tool to support urban water decision making but some important technical issues are often overlooked for the sake of simplicity. This may jeopardise the potential benefits that MCDA has to offer.***

The Water Services Association of Australia (WSAA) sustainability framework is a good indication of the potential role that MCDA can play in urban water management decision making (Lundie *et al.*, 2008a). However, the usefulness of these frameworks is uncertain because there are gaps between the challenges in real world decision making and the underlying formal mathematical theories behind MCDA approaches. As discussed in Chapter 1 (introduction), there are many barriers to successful implementation of decision support frameworks, including both the ‘hard’ factors (e.g. technical issues) and the ‘soft’ factors (e.g. institutional factors such as values, knowledge frameworks etc.). This thesis identified and addressed four methodological shortcomings (i.e. hard factors) associated with the WSSA decision model (Phases 3, 5 and 6 of WSSA framework). They were (1) double counting, (2) judgement uncertainty, (3) criteria interaction and (4) range sensitivity.

This thesis set out to answer the following research questions in relation to the four shortcomings identified:

- How to avoid <u>*double counting*</u> in urban water management decision problems?
- How to account for <u>*judgement uncertainty*</u> in urban water management decision problems?
- How to account for <u>*criteria interaction*</u> in urban water management decision problems?
- How to avoid <u>*range sensitivity*</u> in urban water management decision problems

The following summarises the problems associated with the four shortcomings and highlights the solutions to each of the stated research questions. Findings from the research using the proposed solutions are also summarised to discuss whether the proposed solutions can improve decision analysis or not.

<u>*Double counting*</u>

Problem

The problem of double counting occurs when the chosen criteria are at least partly redundant and the key criteria are not included respectively (Schankerman, 1981). There are a number of problem structuring methods that address the problem of criteria selection by advising how to develop criteria such as Friend and Hickling's (2005) Strategy Choice approach, Eden and Fran's SODA (1989) and Eden and Ackermann's (1998) journey making. However, it was found in the literature review (Section 2.5.1 p.39) that the majority of the publications did not adopt any decision support framework to assist in the selection of criteria, only a quarter of the reviewed publication did. A potential issue would be double counting if the criteria were not carefully selected. Double counting was identified in five long-term water strategies in Australia (Section 2.5.1 p.45).

Solution

- ***Double counting can be avoided by careful criteria selection***

Value focused thinking (Keeney, 1996) can be used to avoid double counting. The technique begins with identifying the fundamental criteria and connects the related means-ends criteria. Fundamental criteria are those that reflect the fundamental objectives in the decision context whereas means-end criteria elaborate the means by which the fundamental values occur. Double counting occurs when the means-ends indicators are inadvertently included in the fundamental criteria. Very often the differentiation between these two types of criteria is not made in structuring decision problems (Keeney, 2002).

The author applied the concept of '*from and to*' to identify the flow of relationship between fundamental and means-ends criteria as opposed to the traditional criteria tree that is grounded on '*is*' and identity. Fundamental criteria represent the values of the DMs (from) which the means-ends criteria are connected to because they represent the means that by which the fundamental values are influenced (to). Once the fundamental and means-ends criteria are identified, a relationship diagram can be constructed to illustrate the relationships between the two types of criteria. DMs can check the relationships between the selected criteria to identify any misplaced means-end criteria in the fundamental criteria hierarchy.

Improved decision analysis results?

As the saying goes, 'A properly framed question is half the decision made'. Although it is beyond the scope of this thesis to validate the impacts of better criteria structuring, the author highlights a benefit in applying value focused thinking. Common understanding of the constructed criteria hierarchy among the DMs is very important. Different people can interpret the structure of the criteria hierarchy differently. As an example, a participant in the case study commented on the hierarchy of technical criteria (*security of supply, reliability of services, flexibility and risks*). The participant made a comment about the security of supply as the starting point for investment rather than 'post-factors' such as flexibility, reliability of services and risks. As a result, the participant placed a very high emphasis on security of supply to reflect this point of view. The participant in the example interpreted security of supply as the fundamental criterion and the rest as means-ends indicators contributing to the success of security of water supply.

Irrespective of the correctness of this interpretation, there is a very important message that emerges from this comment. Different understanding of the criteria structure directly affects the DMs' judgement to make trade-offs between the criteria. Therefore it is important for the DMs to have a common interpretation of the criteria value tree. By differentiating the between fundamental and means-ends criteria, DMs can identify any common or disparate interpretation or/and understanding.

Judgement uncertainty

Problem

Uncertainty in decision making can be classified as internal and external (Friend and Hickling, 2005). Internal uncertainty is related to imprecise judgement and external uncertainty is related to the lack of knowledge about consequences of actions. External uncertainty has received a lot of attention because this type of uncertainty can be modelled with relative ease using the theory of probability. Judgement uncertainty under internal uncertainty, in contrast, has received little attention. From the literature review, it was found that majority of the publications address the uncertainty associated with criteria weights judgement and criteria scores assignment with only sensitivity analysis (Section 2.5.1 p.39).

Solution

- ***Fuzzy set can be used to account for judgement uncertainty***

To account for judgement uncertainty in urban water decision problems, fuzzy set theory can be applied. The reader can refer to Section 4.3.2 p.153, Section 5.3.2 p.201 for details and Appendix D1 for explanations of fuzzy set theory. In essence, the two important inputs in the preference models, 'criteria weights' and 'criteria scores' can be described as fuzzy sets which replace the conventional discrete real numbers. The fuzzy criteria weights and fuzzy criteria scores can be aggregated using the fuzzy simple additive weighting (FSAW) technique to produce a global value for each alternative.

Improved decision analysis results?

Although it is beyond the scope of this thesis to justify the FSAW approach using statistically valid results, the outcomes from the case study have provided very insightful knowledge to the way DMs consider uncertainty in their judgement. The conclusions are drawn from the key results identified in Section 5.4.6 p.236

- ***Key result 1: The level of understanding of the decision problem by the DMs directly affect their 'internal' mode of aggregation***

The results from the case study showed that as DMs became more familiar with the decision making problems, they moved away from using averaging functions as their preferred aggregated model and FSAW became the more preferred aggregation model. This was evident through the improved correlation between the observed global values and the calculated global values obtained by FSAW in the case study (Table 5.18). This suggested that the influence of judgement uncertainty became stronger as DMs were more aware of the issues and the uncertainty involved. Their judgements became more imprecise.

Therefore, the role of a decision support tool is not to find the most 'suitable aggregation model' because DMs' preferred mode of aggregation changes with their understanding of the problem. Rather, a suitable aggregation model is dependent on the DMs' level of understanding of the problem. If the DMs are not familiar with the decision problem (e.g. at the beginning of the decision making process), they tend to use direct averaging aggregation functions such as ordered weighted averages or median as their preferred mode of aggregation. If the DMs are more familiar with the decision problem, they tend to consider more factors. These factors may not be fully known to the DMs and as such, DMs' judgements become less precise. In this case, FSAW is a more suitable aggregation method that takes into account judgement uncertainty.

- ***Key result 2: Ordered weighted average is a suitable surrogate for weighted average if no uncertainty is involved***

OWA ranked consistently better than weighted average in modelling the observed global values as shown in Table 5.17 and Table 5.18. This suggested that weighted average might not be the most suitable averaging function, although it was the most widely applied aggregation function. If no uncertainty was considered, OWA could be used as a surrogate to provide a quick initial approximation.

Sensitivity analysis

The sensitivity analyses for Case 2 (FSAW) showed that the results were not very sensitivity to the shape or minor changes to the defined membership function of the fuzzy numbers (Section 5.5.2 p.240). Only minor changes were observed in the correlation for the modified scenarios (Table 5.21). The shape and the defined membership functions could be 'fine-tuned' to better model DMs' preferences.

Criteria interaction

Problem

Criteria interaction is a problem encountered during the preference elicitation stage in which the preference between two criteria can be dependent on the levels of other criteria. Hence under this situation, the preference between two criteria cannot be established without consideration of other criteria. This condition violates the preferential independence assumption associated with the simple additive weighting aggregation model[24], which is widely applied in urban water management. Nearly all publications that were reviewed did not consider criteria interaction (Section 2.5.1 p.39).

Solution

- ***Choquet integral can be used to account for criteria interaction***

To account for criteria interaction in urban water decision problems, the aggregation function, Choquet integral was applied. The reader can refer to Section 4.3.3 p.166, Section 5.3.3 p.219 for details and Appendix D2 for explanation of the Choquet integral. In essence, the relative importance of criteria (criteria weights) is expressed by two parameters, namely Shapley index and interaction index. The Shapley index represents the contribution of a criterion to the overall decision and interaction index is a measure of the positive or negative interaction between criteria. These two parameters together with the criteria scores are aggregated using the 2-additive Choquet integral to produce a global value for each alternative.

[24] The preferential independence assumption is associated with the MCDA approach, value theory. SAW is one of the most common preference models under value theory. Refer to Section 2.6.3.3. for further explanation of this assumption.

Improved decision analysis results?

- ***Key result 3: DMs' understanding of the interaction between criteria directly affects the usefulness of Choquet integral***

A similar observation made in the results for judgement uncertainty (p.250) was also identified in the results for criteria interaction. As DMs became more familiar with the decision problem and were more aware of the interactions between criteria, DMs moved away from using averaging function to Choquet integral as the preferred model. Choquet integral outperformed all the other aggregation functions in modelling DMs' observed global values in the technical category. This was evident through the improved ranking of Choquet integral and fuzzy Choquet integral in the technical category compared to the ecosystem category (Table 5.18). This led to a new observation in which the ability of the Choquet integral to model criteria interaction was dependent on the participants' understanding of the criteria interaction.

Sensitivity analysis

The sensitivity analyses for Case 3 (Choquet integral) showed that the results were sensitive to the strength of preferences. This was evident through the progressive drop in correlations between the observed and calculated global values dropped as the strengths of preference deviate from the original figures. This suggested that the analysed global values were sensitivity to the strength of preference. Therefore, more attention should be paid to ensure that the strengths of preference are consistent during the elicitation process.

Range sensitivity

Problem

A common mistake is to assume that criteria weights are independent of the criteria measuring range. DMs are generally willing to specify the relative importance of criteria on numerical scales without understanding the consequences (Keeney, 2002). However, the assignment of weight is directly related to the method of standardising the criteria scores (Fischer, 1995). This range dependence of weights is referred to as range sensitivity. A number of the long-term water strategies used a generic scoring scale (poor to good) to represent the range for the criteria (some for both qualitative and quantitative), without addressing the specific range for each criterion (Section 2.5.5 p.55). Also a majority of the reviewed journal publications adopted a direct assignment method using either a numerical scale (0–1 or 0–100 point) or a qualitative scale (extremely good to extremely bad) to rate the importance of the criteria (Section 2.5.1 p.39). Most of the current practice in urban water management does not take in account range sensitivity and worst still, evaluation of the relative importance of the criteria are often made independent of the criteria range.

Solution

- ***Use mitigation value trade-off to avoid range sensitivity***

A new technique was developed which is used to elicit criteria weights based on the mitigation concept (see Section 4.2.10 p.126). This technique involves making trade-offs in terms of the level of mitigation a DM is willing to undertake to minimise the impact of a criterion. The consequences of the trade-offs involved are made explicit to the DMs by stating the various possible impacts for all criteria if different levels of mitigation are undertaken. Construction of a qualitative scale is commonly applied to measure a criterion. By characterising the criteria with a series of mitigation levels, DMs can assign criteria weights with reference to a known measuring scale based on the level of mitigation. In this way, the reference points can defined to the global scale and avoid range sensitivity.

Another innovation introduced as part of this research is the mitigation normalising function, which is a new technique to normalise criteria scores (Section 4.2.20 p.133). The technique uses the elicited mitigation value trade-off as the mid-point to define the mitigation normalising function.

Improved decision analysis results?

Important potential compromises can be hidden using weighted averages because they tend to generate extreme solutions for the cases with pairs of criteria that are dramatically opposed (e.g. high performances on certain important criteria and relatively poor performances on less important criteria) (Stewart and Scott, 1995). A benefit of the mitigated normalising function is that it minimises over-domination of alternatives with high criteria scores for the important criteria. Also this method allows relatively unimportant criteria with poorer performance to still have some influence over the decisions because the combination of the low scores and high weights balances each other out (Section 4.2.20 p.133, Figure 4.4 (a) and (b)). An added benefit is that it minimises burden on DMs for eliciting the midpoint values to derive value functions in addition to the mitigation value trade-off to derive weights.

6.3 Summary of findings

The conclusions reached in this study regarding the developed decision support approach in addressing the four identified shortcomings can be summarised in the following statement.

- ***The selection of an appropriate preference model is critically related to the DMs' level of understanding the decision problem.***

The following elaborates on this conclusion statement.

- This finding is consistent with a number studies in relation to the comparison of MCDA in that there is no consistent preference for one MCDA method (Belton, 1986; Hobbs *et al.*, 1992; Salminen *et al.*, 1998).
- The influence of judgement uncertainty becomes more important as the decision making process develops. As DMs are required to make trade-off judgements for assessing their preferences, more information is needed in order for the DMs to be fully informed of all possible consequences of actions. However, it is not always possible to provide all the required information and under this situation, DMs are forced to make rough or imprecise trade-off judgements. Fuzzy simple additive weighting is a more appropriate tool compared to averaging functions to model DMs preferences under this type of situation.
- A preference model using the Choquet integral is more appropriate when DMs become more aware of the interactions between criteria during the course of the decision making process. In addition, the ability of the Choquet integral to model DMs' preference model depends heavily on DMs' understanding of the interaction issues.
- An averaging function such as Ordered Weighted Average serves as a good approximation to DMs' preference, if no uncertainty is involved.

6.4 Outcomes of the thesis

A practical outcome of this thesis is a developed decision support approach which offers four decision support methodologies for DMs to choose from. These four approaches cater for different situations encountered in urban water decision problems. The four situations available in the decision support approach are shown in Table 6.1.

Table 6.1 Four DSMs offered in the decision support approach

Situations where DSMs are applicable	Assumptions	DSM
DMs have not considered trade-offs and criteria interaction deeply	No judgement uncertainty and no criteria interaction	Averages functions (e.g. classical averages, median and OWA)
DMs are required to make trade-off judgements with insufficient information	Judgement uncertainty but no criteria interaction	Appropriated fuzzy simple additive weighting
DMs are more aware of the interactions between criteria	Criteria interaction but no judgement uncertainty	Choquet integral
DMs are aware of criteria interaction and are required to make trade-off judgements with insufficient information	Both criteria interaction and judgement uncertainty	Fuzzy Choquet integral

The schematic of the decision support model is illustrated in Figure 6.1.

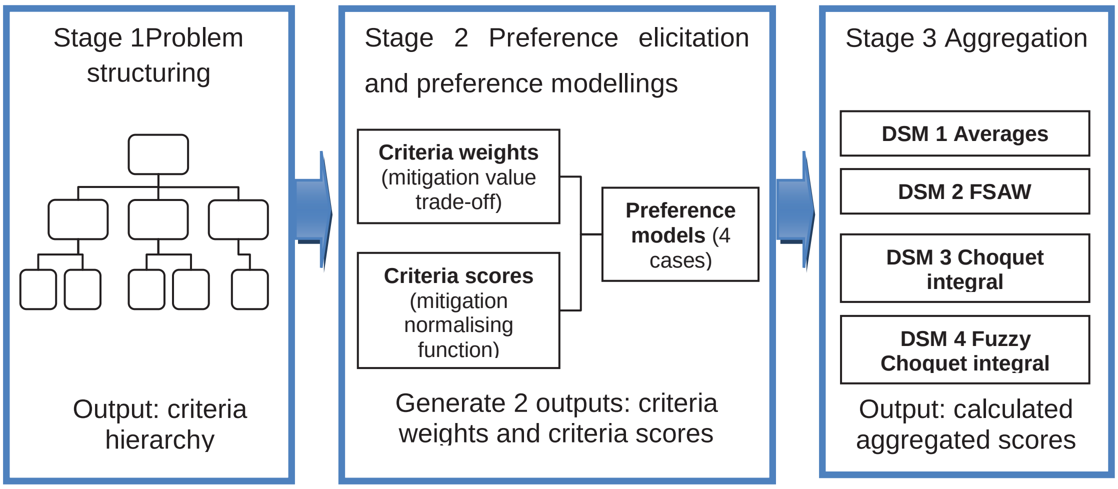


Figure 6.1 Schematic of decision support approach

Although this decision support approach is developed in the context of urban water management, this has a wider application to decision making problems in other fields. The practical application of this research is to provide DMs, particularly in the water industry, with a stronger set of tools which incorporate a modified more rigorous MCDA which overcomes the shortcomings in the current conventional weighted additive approach.

6.4.1 Mitigation value trade-off

A key novelty developed as part of this study is the mitigation value trade-off which is a technique for deriving criteria weights for decision making problems. It is particularly useful in the situation when DMs want to highlight the trade-off in comparing the different criteria. Like all other criteria weighting methods, some care should be taken into account when applying this technique. The following points should be carefully considered when applying the mitigation value trade-off:

- ***Who and how to generate the mitigation options*** - the set of mitigation options should be devised in the context of the decision making problem (i.e. realistically achievable). The mitigation options for each criterion should have the same type of mitigation measure but with more or less in value of the same single mitigation measure. These variable value packages of mitigation for each criteria should be generated by the advisory committee through discussion.
- ***Mitigation value trade-off is fundamentally different from contingent valuation*** - associating a fixed value to the $1,000,000 would potentially delineate this mitigation value trade-off approach to contingent valuation. Therefore, the DMs are not expected to have a sensible market value of $100 or $100,000 for what they can buy. Instead the DMs must think in terms of the ability that this $1 million can do. A million can eliminate a single impact from a criterion entirely. A $50,000 can eliminate 50% of the problem associated with a criterion (or impact), $20,00 can eliminate 25% of the problem, and henceforth. The method contingent valuation relies on people's perceived valuation of the non-marketable goods. Mitigation value trade-off avoids using market value to rate the importance of the criteria, thus eliminating all the well-known challenges associated with contingent valuation. Instead, mitigation value trade-off uses a relative scale to establish criteria preferences by asking the question, "To what percentage do you (the DM) want to eliminate this problem?". A key assumption which allows different criteria to be compared using this logic is commensurability. Commensurability is a fundamental assumption in value

measurement that allows criteria with lower performance to be compensated by better performing criteria.

6.4.2 Mitigation normalising function

The other key novelty is the mitigation normalising function, which is a function that transform the criteria scores to the normalised criteria scores. The normalised criteria scores are used to make comparison between performances of different criteria. This new normalising technique is based on Keeney and Raiffa's (1976) mid-point technique which is used to derive value functions. The following points should be carefully considered when applying the mitigation normalising function:

- ***Significance of the mid-point*** - the elicited mid-point in interpreted as the trade-off level the DMs are willing to accept for a criterion. The midpoint value reflects an acceptable trade-off such that the DMs are willing to give up on the performance of a criterion in order to gain performance in another. This midpoint can be interpreted as the performance level the DMs are willing to accept for that criterion.
- ***Refine the mitigation normalising function by midvalue splitting*** **–** extra midpoint values can be obtained by further breaking the mitigation normalising functions into segments. This can also be used as a consistency check to make sure the DMs are providing consistent evaluations of their trade-off values. The procedure is detailed in Section 4.2.2 p.133.

6.5 Limitation of the decision support approach

The following limitations of the developed decision support approach are listed:

- The technique mitigation value trade-off is not applicable in all situations to elicit criteria weights. In particular, some DMs prefer to express their preferences in the form of ranking and not numerical values. This was evident in the case study in which some participants could not provide mitigation value trade-offs in the form of numerical scores even though the consequences were made clear to the participants in quantifiable terms. They preferred to give preferences to criteria in the form of ranking for reasons unknown to the author.
- The fourth DSM offered under the decision support approach, fuzzy Choquet integral is still relatively undeveloped. Judgement uncertainty is only accounted for in the criteria scores and not in the assessment of the criteria weights (i.e. Shapley index and interaction index). This does not capture the true spirit of the situation in

which judgement uncertainty affects the expression of preferences for criteria with interaction. The problem with the approach as proposed by the author is that the fuzzy criteria scores are defuzzifed back into crisp numbers. This does not make a lot of difference to the original Choquet integral approach but the only change is that criteria scores are normalised using fuzzy sets.

- The purpose of conducting the GCWF case study was to test-proof the developed decision support approach. Although the results of the case study showed that the two DSMs (FSAW and Choquet integral) improved the quality of decision analysis outputs, the study population was not large enough to validate these two approaches statistically.

6.6 Recommendations for further research

Significant contributions have been made from developing the decision support approach, but there are still a number of research directions which could further enhance the value of the framework. The following recommendations have been identified:

- Validate the approaches (the three DSMs) statistically – a similar study like the GCWF case study can be conducted but with a larger study population. The study population is preferably professionals from the field of urban water management. This would provide a stronger foundation for validating the approaches.
- Further develop the fourth DSM (fuzzy Choquet integral) – the combination between fuzzy set theory and Choquet integral provides a promising solution to the situations where criteria interaction and judgement uncertainty are considered in the decision making problems, particularly in the field of urban water management.
- Incorporate this decision support approach into a truly integrative sustainability framework such as the WSAA's sustainability framework (2005) — WSAA's sustainability framework provides guidance on stakeholder involvement. The developed decision support approach in this research only deals with the technical components. A truly integrative sustainability assessment framework should be holistic by including guidelines for stakeholder engagement. The value of this research is in improving the technical modelling component of an integrated sustainability assessment for urban water management.

Appendix A. Decision Support Methodologies

At the heart of MCDA is the DSM. Selecting an appropriate MCDA approach depends on the selection of the DSM. Since MCDA approaches differed by their DSM, the types of DSM can be classified by: 1) utility theory; 2) outranking methods; 3) non-classical approaches and 4) goal programming. The first approach belongs to MODA and the last three approaches belong to MADA. The focus of this research was on MADA because in urban water decision problems, there are finite numbers of alternatives involved. Nonetheless, this review offers a snapshot of commonly used MCDA approaches for urban water application. It is beyond the scope of this review to present all available MCDA methodologies. For in-depth details, Figueira *et al.* (2005) offers a state-of-the-art review of MCDA, including methodologies, applications and software.

A1 Value measurement

Value measurement has its root in utility measurement. The theory of utility measurement is a formal justification for an individual's preference which can be described as the maximisation of the expected utility, or more generally speaking, associate a real number to each alternative in order to produce a preference order on the alternatives. von Neumann and Morgenstern's (1944) expected utility theory allows the expected utility, which is measured by a utility function, to be added and multiplied by real numbers. Early works in formalising the additive von Neumann and Morgenstern utility function in multi-criteria decision problems were contributed by Pollak (1967) and Fishburn (1970). Their works allowed the utility of an individual's preference to be calculated as a linear combination of part utility by making an important assumption: *preferential independency* between criteria (the implication of this assumption is explained further in Section 2.5.4 p.54). Hence, the widely used form of preference model, the simple additive weighting (SAW) model was enabled:

$$v(a) = \sum_{i=1}^{m} w_i x_i(a) \qquad \text{A-1}$$

where

v(a) is the overall utility of alternative a

w_i is the weight associated with the importance of criterion *i*

$x_i(a)$ is the utility reflecting alternative *a*'s performance on criterion *i*.

There are four utility methods that are based on this additive model:

1. Multi-Attribute Utility Theory (MAUT) and Multi-Attribute Value Theory (MAVT)
2. Utility Theory Additive (UTA)
3. Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP)
4. Measuring Attractiveness by a Categorical-Based Evaluation TecHnique (MACBETH)

A1.1 Multi-attribute utility theory and multi-attribute value theory

The popular MAUT formalised by Keeney and Raiffa (1976) is a single synthesising criterion approach that reduces all criteria to a single criterion for comparison. It assumes the DM's preference for each criterion can be represented by a utility function (involves unknown consequences) or a value function (involves known consequence). The difference between the two approaches led to the separation between MAUT and MAVT. To differentiate between the two, the form is referred to as the *utility theory* and the latter refer to as *value theory*. These two approaches differ by the types of preference functions utilised as explained in the following.

At this point, there is a very important differentiation to be made between utility theory and value theory. The term utility implies preference under risks which involve uncertainty modelling that is specifically represented by the method MAUT (criteria scores measured by probabilities). In contrast, the term value implies preference under certainty which is similarly represented by the method Multi-attribute value theory (MAVT) (criteria scores measured by real scalar numbers).

Although the author is not concerned about the selection between MAUT and MAVT here, these two terms utility and value imply two different meanings. Therefore these two terms need to be clarified and used specifically for their own reasons. As discussed, the term utility implies the involvement of external uncertainty[25] which is modelled in the form of lottery estimation (the likelihood of a random event happening). Since the scope of this thesis is to model internal uncertainty related to judgement[26], the term utility is therefore not appropriate. With this perspective, the author uses the term value theory instead of utility theory with a more precise meaning.

A1.1.1 Preference under uncertainty (utility theory)

Let $x_1, x_2, \dots, x_i$ be the possible performance level or consequence of a criterion and let x^* be a most preferred consequence and x^o be a least preferred consequence (i.e. $x^* = 1$ and $x^o = 0$). A utility function involves the assessment of each performance level *x*, a probability p such that x is indifferent to the lottery (x^*, p, x^o), yielding a probability p at x^*, and x^o at *1 – p*. In another word, the assessment involves finding out a probability of the lottery[27] (x^*, p, x^o), such that the DM is indifferent between the two performance levels x and x^*. The procedure involves the assessment of a few performance points as above and then fitting a curve, which becomes the utility function. The expected utility derived for each consequence is a measure of its relative desirability. The preference function which is derived using this model is called the *utility function*.

A1.1.2 Preference under certainty (value theory)

In the same spirit of the utility function, a value function is used to model DM preference. The preference function which is derived using this model is called the *value function*. The main difference lies with derivation of the functions. The philosophy behind value functions is that the preference towards a consequence *x* can be measured by a real number value $v(x)$, in which the higher the numbers, the more preferred is the consequence. The measurable value function can be assessed by direct rating of criteria in the form of criteria weights or finding out the strength of preference between criteria.

In contrast to the utility function, value functions do not required choice among lotteries which can be difficult to understand and cumbersome for the DM. The use of utility function is not as common as value function predominately due to the reasons stated

[25] The different types of uncertainties are discussed in Section 2.5.3.
[26] An outline of the scope of research is introduced in Chapter 1 and also subsequently in Section 2.5.3 with greater details.
[27] Lottery refers to the probability in a lottery game such as the flip of a coin.

above. By definition, a utility function is a value function, but a value function is not necessarily a utility function.

The complexity with MAUT/MAVT is the assignment of appropriate utility and value functions. There are a number of methods to derive utility and value functions. A comprehensive list of utility assessment methods can be found in Farquhar (1984). For value functions, refer to von Winterfeldt and Edwards (1986) and Kirkwood (1996). In particular, an elegant form of a value function is Edwards and Barron's (1994) Simple Multi-Attribute Rating Technique (SMART) which uses simple additive weighting method as the utility function. The methods AHP and ANP are often loosely referred to as MAVT approaches in some literature because they have many similarities with MAVT (Belton, 1986).

A1.2 Analytical hierarchy process and analytical network process

The analytical hierarchy process (AHP) provides a basis for analysing complex decision problems by arranging criteria into a hierarchy. The relative importance of the criteria are determined through pairwise comparison of alternatives and converted into a set of weights. The logic of the pairwise comparison is as follows: "with respect to a criterion (c_i), which of the two alternatives *a* or *b* do you prefer?". The DM is asked to indicate the strength of his/her preference between the two alternatives *a* and *b* using the following scale, in which intermediate values can be used:

1 Equally preferred
3 Weak preference
5 Strong preference
7 Demonstrated preference
9 Absolute preference

If there are *n* alternatives, to obtain the complete set of pairwise comparisons, n(n-1)/2 comparisons are required in total. The judgement obtained using pairwise comparisons are summarised in a pairwise comparison matrix as shown in Table A.1. The pairwise comparison matrix can be reduced to a comparison vector (i.e. a set of scores for each alternative) by taking the matrix's eigenvector, representing the relative performance of each alternative. The relative weights of the criteria are determined by obtaining the eigenvalues of the pairwise comparison matrices. Applying the simple additive weighting method to the eigenvectors and eigenvalues, the ranking for the alternatives are derived. Criteria that are both intangible and tangible are compared by incorporating judgement and personal values, increasing AHP's capacity to be a framework for engaging stakeholders (Saaty, 1982; Saaty, 1994a).

Table A.1 An example of a pairwise comparison table with respect to a criterion c_i

Alternatives	a_1	a_2	…	a_n
a_1	1	s12	s1x	s1n
a_2	1/s12	1	s2x	s2n
⋮	1/s1x	1/s2x	1	sxn
a_n	1/s1n	1/s2n	1/sxn	1

Note: s can be the scale value 1, 3, 5, 7, 9 or intermediate values.

The analytical network process is an extension of AHP developed by Saaty (2004a; Saaty, 2004b; Saaty, 2004c) that deals with dependency between criteria and objectives in decision making problems. The theory depends on the values and judgement of an individual or group to assess dependence. AHP with its independence assumptions is a special case of the ANP. In ANP, networks are built to model the links between depending criteria instead of hierarchy used in AHP. ANP overcomes the limitation of linear hierarchic structures and their mathematical consequences.

The strongest debate against the use of AHP is perhaps the problem of rank reversal (Belton and Gear, 1983; Barzilai and Golany, 1994). This issue refers to the fact that under certain situations, the introduction of a new alternative with no changes to the original criteria performance range may lead to a change in the ranking order of other alternatives. Much effort is placed on the avoidance of rank reversal, or to provide guidance to preserve the rank order (Schenkerman, 1994; Millet and Saaty, 2000). Belton and Stewart (2005) explained that the phenomenon is natural with the AHP process as the weight assessment changes when a new alternative is introduced. This is because AHP utilises a ratio score which sum up to 1 for each criterion. This means that the weights of the criteria are the relative worth of the *total* score. Hence, the scaling of the score naturally changes when an alternative is added or deleted. The relative importance of the criteria should be modified if there are any changes to the alternatives. In contrast, direct weighting on the interval scale in between 0 and 100 is used in MAVT so that the weight of each criterion is a relative worth of the swing in between 0 and 100. The trade-off rationale behind the scoring method of AHP is not immediately apparent to the DM. Although the issue of rank reversal can be justified or managed, the rationale behind the modification may not be easily conceptualised to the DM. From this perspective, MAVT is a more transparent method because the direct rating method is closer to human reasoning.

A1.3 Utilities additive

The UTA method proposed by Jacquet-Lagreze and Siskos (1982) adopts a different approach from the conventional logic of MCDA. In most cases, the decision problem is concerned about the way aggregation of the preference is performed to obtain the computed decision outcome. In UTA, the logic is reversed by assuming that the decision outcome is given, and the task is to find the rationale for the decision being made. This philosophy is labelled as preference disaggregation, in contrast to the conventional preference aggregation logic.

Suppose the DM is able to express a definite preference for an alternative *a* over another alternative *b*, but the alternatives can be hypothetical which may be easier for the DM to rank. In this case, the hypothetical alternatives formed a subset or reference set of the actual set of alternatives. The preference on the reference set is extrapolated to a reference ordering of the full set of real alternatives. A linear program is applied to evaluate the utility functions of each criterion in which the parameters of these functions are determined to be consistent with the extrapolated preference order.

This approach is suitable for the situation where there is a relatively large set of real alternatives for the reference set to choose from. The outcome is dependent on the choice of reference set and the familiarity of the DM to make the preference on this reference set, which is an issue that needs to be considered in the application of this method.

A1.4 Measuring attractiveness by a categorical-based evaluation technique

Measuring attractiveness by a categorical-based evaluation technique (MACBETH), developed by Bana e Costa and Vansnick (1994), is a method that uses linguistic interval scales in a pairwise comparison manner to establish preference between alternatives. This method avoids forcing the DM to give direct numerical representation of their preference, which can be difficult for the DM depending on their ability to quantify understanding of the subject matters (Bana e Costa and Vansnick, 1997).

Based on an iterative workbook procedure that only requires qualitative judgement input, a quantitative value model is built. The qualitative judgement is assessed from a linguistic interval value scale which is divided into six intervals: ‘very weak’, ‘moderate’, ‘strong’, ‘very strong’ and ‘extremely strong’. These six intervals are represented by non-overlapping intervals of real numbers.

To obtain the criteria performance scores for each alternative from the ordinal inputs, MACBETH adopts the following procedure:

1. For each criterion, a scale of preference is established by first defining two anchors, which can be the most and the least attractive options with regards to the criterion in consideration.
2. The most and least attractive options are given a weight such as 100 and 0 respectively.
3. DMs are asked to rate each of the remaining options with a preference value from the interval scale that reflects the attractiveness of that option relative to other options (i.e. ‘very weak’, ‘weak’). A performance score is generated for each option based on its position in the scale of preference.

To obtain the criteria weights, MACBETH adopts the following procedure:

1. Since the two anchoring points are established for each criterion, DMs are asked to consider for an option in which all of the criteria are at their least attractive levels, how much would a swing from the worst to the best level in a particular criterion increase its overall attractiveness?
2. DMs are then asked to rate the difference in attractiveness between the swings. It begins with the comparison of the most attractive swing to the second most attractive swing and so forth. The criteria weights are determined based on the relative rating between the swings.

The criteria weights and scores are aggregated using the weighted sum model (Eqn 2-1) to obtain overall ranking for the alternatives. MACBETH is an approach that considers the synergistic effect of a pair of criteria when establishing criteria preferences within the field of utility theory. Another benefit is that it only requires ordinal inputs, and thus is suitable for applications in which DMs can only offer ordinal judgement. However, the down side of this is the cumbersome questioning process which can introduce inconsistency in judgement. Although there are procedures to ratify any inconsistency, the intrinsic meaning behind the judgement may differ from the final value functions.

A2 Outranking

The outranking approach seeks to find a compromise for comparing alternatives by balancing the relationship between the alternatives' poor performing criteria and well performing criteria (Roy, 1991). The ELECTRE (ELiminiation Et Choix Traduisant la REalite) method was the first method to use the outranking approach developed by Bernard Roy in the late 1960s. All methods using the outranking approach include two phases: 1) construction of outranking relationships; and 2) exploitation of the outranking relationships (Brans *et al.*, 1984). The ELECTRE method uses pairwise comparison to evaluate the outranking relationship. Through assessing alternatives via outranking relationships, the dominated alternative is eliminated and the method seeks to find an alternative that is at least as good as the others for the majority of the criteria.

Two concepts in ELECTRE are used to exploit the outranking relationship, concordance and discordance. Concordance reflects the degree to which alternative *a* is more important than alternative *b* based on the criteria that alternative *a* outperforms *b*. Discordance reflects the degree to which alternative *a* under-performs compared to alternative *b* based on the criteria that alternative *b* outperforms *a*. These two concepts are used to evaluate the outranking relationships. A family of ELECTRE methods (I, IS, II, III, IV, TRI) have been developed over time.

PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) is a valued outranking method developed by Brans *et al.* (1984) that has its roots in ELECTRE. It aims at reducing the constraints with ELECTRE as outlined above by providing a more transparent methodology. The outranking index is determined by the positive (i.e. strength of the alternative) and negative (i.e. weakness of the alternative) preference for each alternative. The results are presented in a graphical format and there are two strands in the PROMETHEE family for ranking the alternatives: PROMETHEE I provides a partial pre-order with incomparability and PROMETHEE II provides a total pre-order. Some of the limitations with the use of PROMETHEE are highlighted by De Keyser and Peeters (1996). Similar to AHP, ranking of alternatives with PROMETHEE is prone to change if an alternative is added or deleted. Furthermore, the principal concept of outranking: discordance is not taken into account when formulating the outranking relationship.

Other outranking methods include Regime and NAIADE (Novel Approach to Imprecise Assessment and Decision Environments). Regime is a qualitative outranking method developed by Hinloopen *et al.* (1983), applicable in situations when a mix of ordinal and cardinal information on criteria performance is available (Hinloopen and Nijkamp, 1990). The benefit with the Regime method is the capability to take in both ordinal and cardinal information, which contrasts with ELECTRE that can only take in cardinal information. NAIADE, developed by Munda (2005), is another class of outranking approach that deals with multi-criteria problems with imprecise information and involves uncertainty. Instead of utilising weight as the mean to model preference, the criteria preference can be expressed as distance for numerical evaluation or semantic distance for fuzzy or stochastic evaluation. Pairwise comparisons between alternatives are made on the basis of how much better or worse an alternative is compared to the other by the concept of distances.

A3 Other non-classical approaches

There are many other MCDA approaches proposed outside the two main schools of thought (utility theory and outranking under the MADA branch). Figueira *et al.* (2005) reviewed a number of non-classical approaches, and these are summarised as follows:

- *Risk and uncertainty* – uncertainties can be broadly separated between internal (i.e. related to DM value judgement) and external uncertainties. In Section 2.5.3 p.48, these two types of uncertainties are reviewed in further detail, with regards to the shortcomings identified with the use of MCDA. Stewart (2005) suggested four approaches to model external uncertainties (i.e. related to lack of knowledge) including MAUT and some extensions, stochastic dominance concepts; the use of surrogate risk measures; and scenario planning.
- *Decision rule approach* – this approach represents the preference in terms of the linguistic rule ‘if and then’ which stems from the rough set approach (Greco *et al.*, 2001). The benefit is that DMs can express judgement in linguistic terms.
- *Fuzzy set* – internal uncertainties which appear in the form of imprecise and vague human judgement can be modelled using fuzzy set theory. This extension of this approach in MCDA has gained significant success as evident in its wide range of

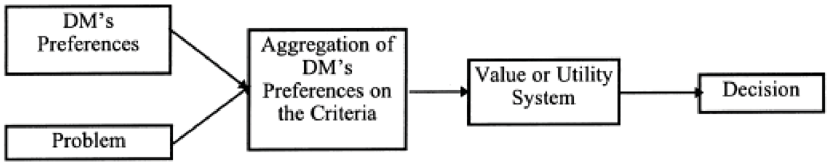
applications in real decision making (Zimmermann, 2001). The extension of fuzzy sets to MCDA is reviewed in greater details in Section 2.6.

- *Fuzzy measures and integral* – a modification of MACBETH is made to adopt a more sophisticated aggregated model that takes account of criteria interaction, using the Choquet integral. Details on the Choquet integral and fuzzy measures are described in Sections 0 and 0 (Grabisch *et al.*, 2003).

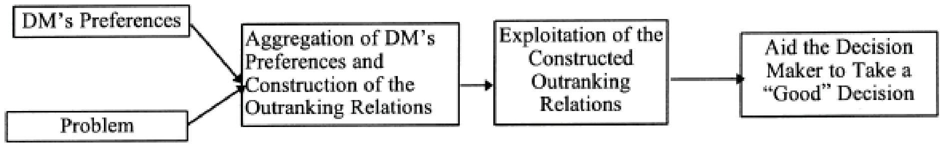
A4 Goal programming

This approach belongs to the MODA branch in which the emphasis is placed on the concept of satisfying. The idea is to achieve satisfactory performance levels for each criterion with the intention to shift to other criteria once this is achieved. Goal programming and its variants are the first attempts at providing formal support for multi-criteria decision problems. Goal programming seeks to achieve a set of objectives simultaneously under a set of constraints that can be linear or non-linear. The underlying principle of goal programming is to eliminate alternatives until a satisfactory level of performance for each criterion is achieved. Value judgements of DMs are expressed in the form of goals for each criterion. There are variants to goal programming such as weighted goal programming for incorporating DMs' preferences on the goals. For general further description of goal programming theory, the reader is directed to Tamiz *et al.* (1998).

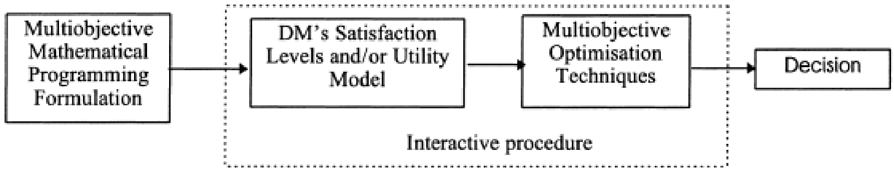
Compromise programming is also an extension of goal programming developed by Zeleny (1973). It is the most widely used method within MODM. The underlying principle is similar to goal programming in which the DM aspires to come as close to the ideal solution as possible by some measure of distance.



(a) Utility theory



(b) Outranking



(c) Goal programming

Figure A.1 Theoretical structure of (a) utility theory (b) outranking (c) goal programming (Siskos and Spyridakos, 1999)

Appendix B. Criteria Weight Elicitation and Criteria Score Standardisation Techniques

There are two main components in applying value theory:

1. *Eliciting criteria scores (x_{ij})* – representing the performance levels for each criterion.
2. *Standardise criteria weights (w_i)* – representing the relative importance of each criterion in a commensurate unit.

The following two sections (D1.1 and D1.2) describe the different methods in eliciting these two types of information.

B1 Standardisation of criteria scores

The standardisation of criteria scores is concerned with constructing partial value functions to measure the relative performance level of each selected criterion. This process of assessing the value of performances of alternatives against the selected criteria can be referred to as the assessment of the *partial value function*, $v_i(a)$ or more commonly known as *standardisation*. It has the property that an alternative a is preferred to b for a criterion if on and only if $v_i(a) > v_i(b)$.

Standardisation is a process of transforming the criterion performance level into a numerical scale according to the DMs' preference. Raw criteria scores are measured by their own natural scales (e.g. cost is measured by dollars and greenhouse gas emission is measured by tonnes of CO2-eq). These raw criteria scores need to be normalised into a unified measuring scale in order to compare the performance of different criteria. Only normalised criteria scores can feed into the value functions to compare alternatives. In order to differentiate between raw criteria scores and normalised criteria scores, the following notations are adopted:

- Raw criteria score (x^*), where $x^* = (x_1^*, x_2^*, \dots, x_n^* \,|x)$
- Normalised criteria score (x), where $x = (x_1, x_2, \dots., x_n | i = 1, 2, \dots, n)$

Prior to constructing a measurement scale to assess the criteria scores, it is important to choose the reference model for the measurement scale. *Reference points* are the two end points of the measurement scale indicating the upper and lower end of the measurement range. Very often 0 and 100 are used as the reference points, but other reference points can be used as well. There are two types of approach to determine the reference points according to Goldstein (1990): *local scale* and *global scale* . The differentiation between the two is detailed in Section 2.6.4.

Once the reference points are determined, the next step is to consider how to assess the other intermediate scores. There are three main approaches:

- *Normalisation or define a partial value function* – this approach requires a partial value function to be defined, in order to relate cardinal value to the criteria's performance level (e.g. $f(x) = kx$).
- *Construction of a qualitative value scale* – the performance level can be assessed by reference to linguistic terms (i.e. low, medium, high)
- *Direct rating of alternatives* – no measurement scale is required for this approach. Each alternative is compared directly to the reference points on an analogue scale. The DM can do so by specifying a numerical value or a position on the analogue scale for each alternative.

B1.1 Normalisation or define a partial value function

There are three main types of partial value functions:

- Monotonically increasing - the partial value function is monotonically increasing against the raw measurement scale (e.g. higher the criteria raw value, the more preferred it is) (Figure B.1 a, c, e)
- Monotonically decreasing - the partial value function is monotonically decreasing against the raw measurement scale (e.g. lower the criteria raw value, the more preferred it is) (Figure B.1 b, d, f)
- Non-monotonic – the most preferred point is the intermediate point on the raw measurement scale. A monotonic value function generally indicates that there are two conflicting values for the measuring the criterion (Figure B.1 g, h).

These three types of partial value functions can be further differentiated by their linearity (i.e. linear and non-linear functions). Different techniques can be adopted to construct linear or non-linear partial value functions.

Table B.1 Different approaches to construct partial value functions

	Linear	Non-linear
Monotonically increasing and monotonically decreasing	Min-max approach Range approach Distance to target	Bisection method Difference method
Non-monotonic	-	Construction of qualitative scale method

B1.1.1 Linear monotonically increasing or decreasing partial value functions

There are three commonly used techniques to normalise criteria scores for linear monotonically increasing and decreasing partial value functions:

- *Min-max approach* – the best performance raw criteria score gets the highest normalised score of 1, while the worst performing raw criteria score is assigned with a normalised score of 0. All the other raw criteria scores in between are interpolated in a linear manner.
- *Ranges approach* – this technique is applicable if there is sufficient information available to define the maximum and minimum boundaries of the criteria raw score. The maximum and minimum raw criteria scores are given a normalised value of 1 and 0 respectively, similar to the min-max approach.
- *Distance to target approach* – the normalised criteria score is measured based on the distance away from an ideal target. This technique involves the assignment of an ideal target (t) that is an achievement of a criterion that DM would like to realise. The technique is summarised as follows:
    - If a raw criterion score has a performance less than the target $x^* < t$:

$$x = \frac{x^*}{d}$$

    - If a raw criterion score has a performance greater than the target $x^* > t$:

$$x = \frac{d}{x^*}$$

These three methods have their own advantages and disadvantages. The min-max method produces a larger difference between the normalised criteria scores as the range is widened by assigning the best x^* with a normalised score of 1 and the worst x^* as 0. This affects the values of final aggregated scores by emphasising the better performing criteria more and less on the poorer performing criteria. The range method is a better choice with regards to this because more appropriate minimum and maximum raw criteria scores are chosen. However, this requires sufficient available information to determine the appropriate maximum and minimum range. This disadvantage also applies to the distance to target approach. Normally for the sake of simplicity, linear functions are applied for interpolating the raw criteria scores. However, Stewart (1993) demonstrated that the results of using linear value function can often generate misleading recommendations.

B1.1.2 Non-linear monotonically increasing or decreasing partial value functions

There are two widely applied techniques to normalise criteria scores for non-linear monotonically increasing and decreasing partial value functions:

- *Midpoint technique* (Keeney and Raiffa, 1976) or *bisection method* (von Winterfeldt and Edwards, 1986) – this technique requires the DM to identify a point which is halfway on the measurement scale. The procedure is as follows:
  - o Two reference points (x_0^*, x_1^*) are first identified using either a local or global scale
  - o Identify a mid-point $(x_{0.5}^*)$ between the two reference points (x_0^*, x_1^*) such that an increase from (x_0^*) to $(x_{0.5}^*)$ is the same as an increase from $(x_{0.5}^*)$ to (x_1^*)
  - o Next, consider these two reference points $(x_0^*, x_{0.5}^*)$. Identify a mid-point $(x_{0.25}^*)$ between the two reference points $(x_0^*, x_{0.5}^*)$ such that an increase from (x_0^*) to $(x_{0.25}^*)$ is the same as an increase from $(x_{0.25}^*)$ to $(x_{0.5}^*)$
  - o The process is repeated to obtain midpoint values such as $x_{0.75}^*$ or additional points x_k^* can be obtained where $k = (0, 1, 0.5, 0.75, 0.25, \dots.)$.
- *Difference method* (Watson and Buede, 1987) – this concept of this method is to elicit from the DM a preference order on different intervals of the measurement scale. The procedure is as follows:
  - o Two reference points (x_0^*, x_1^*) are first identified using a local or global scale

- Divide the criterion measurement scale into *n* intervals (e.g. 4 intervals: $x_0^* - x_{0.25}^*$; $x_{0.25}^* - x_{0.5}^*$; $x_{0.5}^* - x_{0.75}^*$; $x_{0.75}^* - x_1^*$)
- DM ranks the *n* intervals according to increase/decrease in associated value
- The rank order gives an idea of the shape of the curve
- The partial value function can be further refined by asking the DM to assess the relative magnitude of the value increases (or decreases).

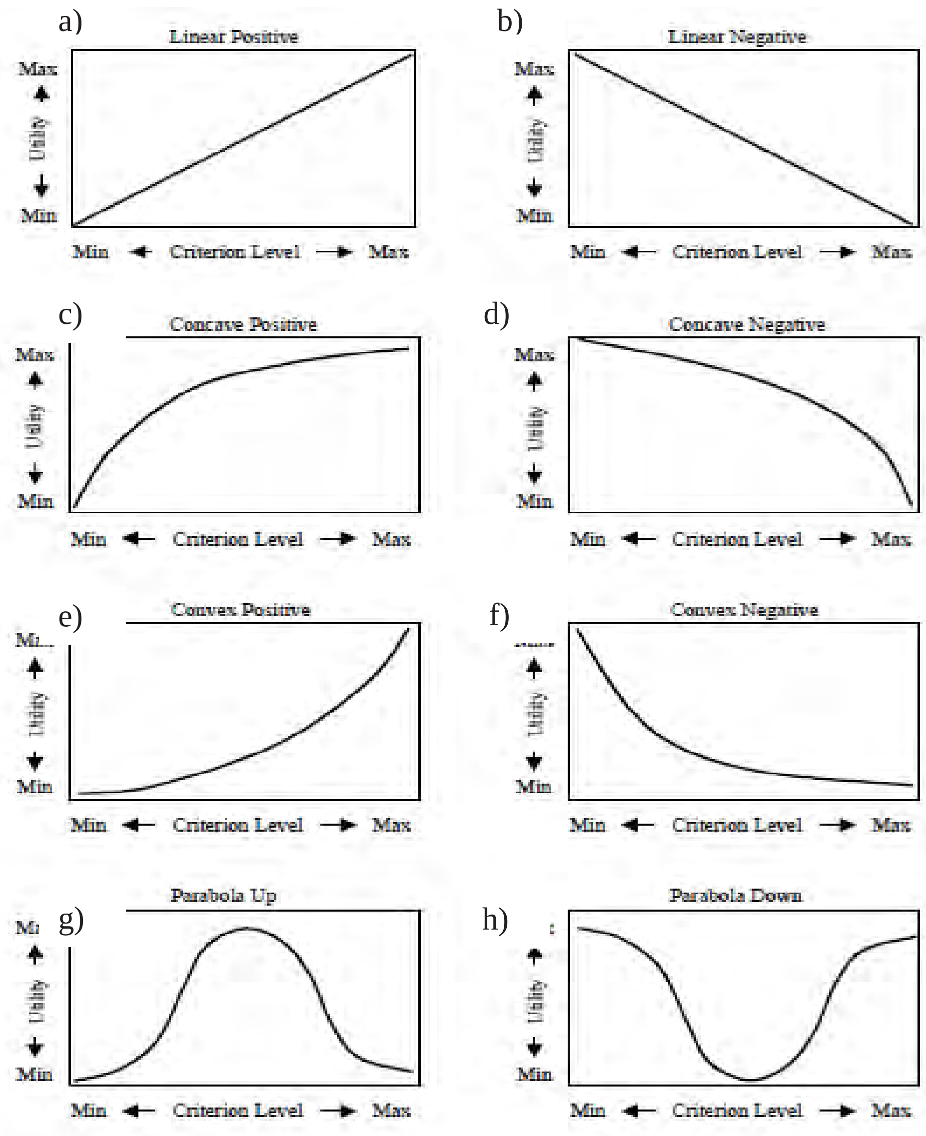


Figure B.1 Generic partial value functions (Hajkowicz et al., 2000)

B1.2 Construction of a qualitative function

Often it may not be possible to construct a partial value function to measure a criterion quantitatively. In this case, a qualitative measurement scale can be used instead. The first step is to identify the two reference points, which can be qualitative in nature. Then, the intermediate points are described linguistically. The MACBETH (Measuring Attractiveness by Categorical-Based Evaluation TecHnique) method (Bana e Costa and Vansnick, 1999) provides a way to build a qualitative function from a category scale by using the difference method. It involves a process of pairwise comparisons requesting ordinal judgement about the preference difference. The MACBETH is further described in Appendix A.

B1.3 Direct rating of alternatives

Rating the alternatives directly with respect to each criterion can be seen as the construction of a measurement scale. If a local scale is used to define the two reference points, the alternative which scores the best is given the highest score (e.g. say 100) and the alternative which scores the worst is given the lowest score (e.g. say 0). The other intermediate alternatives are positioned directly on the scale to reflect their performances relative to the two reference points. The DM is not required to associate a measurable value to the intermediate alternatives. This method is simple and does not require the DM to provide values, but a disadvantage is that if new alternatives are introduced, the scale needs to be redefined. Therefore, the global scale is more appropriate for an iterative process but this requires more work.

B1.3.1 Direct rating by pairwise comparisons

Two popular methods that derive direct rating by conducting pairwise comparisons between alternatives are Saaty's Analytic Hierarchy Process (AHP) and MACBETH. The AHP asks the DM to rate the all possible pairs of alternatives with respect to a criterion in turn. The MACBETH, on the other hand, asks the DM to rate the different intervals of the measurement scale based on pairwise comparisons. These two methods are described in Appendix C. Although the use of pairwise comparisons is popular because it is easy to comprehend, there are some drawbacks which require special attention. One of the main concerns for using pair-wise comparison is consistency in judgement (Saaty, 1994b). Often, the DMs can be confused with the large number of judgement required (e.g. $n(n-1)/2$ for each criterion for n alternatives) and make inconsistent judgements. Therefore, consistency checking is an integral part of using direct rating by pairwise comparisons.

B2 Elicitation of criteria weights

The task involved is to elicit a set of values to represent the relative importance of each selected criterion from the Decision Makers (DMs). The values can either be cardinal (numerical) or ordinal values (ranking). The values are essentially a scaling factor which relates scores to all other criteria.

B2.1 Direct assignment

As suggested by the name, the method requires the DM to assign the weights directly. The DM can either do this in two ways:

1. *By cardinal evaluation* – assign weights quantitatively by using a specified measuring scale
2. *By ordinal evaluation* - simply by assigning rankings.

B2.1.1Cardinal evaluation

The DM uses a pre-defined measuring scale (e.g. 0 to 100 scale) to rate the importance of each criterion. The assigned numerical weights are normalised by diving the sum. This method is referred to as the *cardinal rating method*. A variant to the cardinal evaluation method is called the *ratio method* (Edwards, 1977b; von Winterfeldt and Edwards, 1986). In this procedure, all criteria are first rank ordered in importance. Then, it requires that the importance of the criteria to be evaluated with respect to the least important criterion (i.e. criterion *i* is 3 times as important as criterion *j*). The most important criterion is evaluated with respect to the least important criterion with a value of p_i (i.e. the number of times more important than). The given value (p_i) is turned into a ratio ($1/p_i$) representing the weight of least important criterion. The next most important criterion is evaluated with respect to the least important criterion and the given p_{i-1} is turn into a ratio ($1/p_{i-1}$) representing the weight of the next least important criterion. The procedure is carried on and the weights are normalised to obtain the final weights.

Due to the simplicity of this method, the psychological inertia of the DM can introduce bias into the process and create incoherence in the results. To overcome this issue, Simos (1990) suggested to use cards to assist in the direct assignment process. DMs are asked to rank the cards with the name of the criteria first, and then insert as many blank cards as required to indicate the distance between the criteria cards. Figueira and Roy

(2002) showed that the use of Simos method reduces the range of the weights. Figueira and Roy (2002) introduced a new algorithm based on Simos procedure by using ratio to indicate the distance between the worst and best criteria.

B2.1.2 Ordinal evaluation

The DM is asked to rank the criteria in order of preference. The value of 1 is given to the criterion with the least importance, followed by a value of 2 for the next least important and up to the value n for the most important criterion. Criteria with the same ranking are given a tie and the average value of the ranks given is assigned to the tied criteria. The final weights are normalised based on the given value. This procedure originated from Kendall's (1938) method. This method is simple to use because the DM only have to provide ordinal information without giving precise numerical values. A disadvantage of this method is that it restricts the value interval of the weights. For example, for a decision problem with 5 criteria (n = 5), no weight can be greater than 1/3 or smaller than 0.067 (Pomerol and Barba-Romero, 2000).

B2.2 Swing method

The swing method develop by von Winterfeldt and Edwards (1986) is based on the concept of trade-off. This method is to consider each criterion from its worst value to its best value. The procedure begins with establishing the ranking order of the selected criteria first, followed by assigning the values to them. Assuming that all the criteria are at their worst level (e.g. consider an option which score zero on all criteria), the DM is asked to increase one criterion to its best level while the other criteria remained fixed. The first criterion that he/she chooses is ranked first because this swing gives the greatest increase in overall value. The other remaining criteria are assessed a similar fashion until the ranking order is established. Although it common to choose the extreme points of the criterion's measuring scale as the reference points, it is not necessarily the case. In the MACBETH method, Bana e Costa and Vansnick (1999) define two points, 'neutral' and 'good' as the reference points on the criteria measuring scale. Once the ranking order is established, the DM is asked to compare each criterion in turn with the highest ranking. The criterion with the highest ranking is given a score of 100. The next most preferred criterion is assessed on the scale of 0 to 100. The relative criteria weights are determined in such a fashion. The scores are normalised to obtain final weights.

B2.3 SMART, SMARTS and SMARTER

A different weighting method which combines the cardinal rating method and the ratio method is the Simple Multi-Attribute rating technique (SMART) (Edwards, 1977a). Instead of giving ranking, a cardinal value is given to the least important criterion. Higher values are given to the other criterion depending on the relative importance with respect to the least important criterion. This method does not have problem with restricting the value interval like the ordinal evaluation approach.

A variation to the SMART method is the SMARTS (SMART Swings) and SMARTER (SMART Exploiting Ranks) method. The SMARTS method uses the swing method to approximate the weights and then uses the additive weighted sum to obtain the global value for an alternative. In the SMARTER methods, the rank centroid method (Solymosi and Dombi, 1986) is used to elicit the weights. The rank centroid method requires the DM to first rank the criteria in order of preference (r_i). Then, the weight of criteria i associated with the ranking position r_i is evaluated as follows given that there are n criteria:

$$w_i = \frac{1}{n}\sum_i \frac{1}{r} \qquad \text{B-1}$$

B2.4 The entropy

The central idea of this method is that a criterion's relative importance is measured by its entropy or 'dispersion'. This method does not rely on DM's judgement and therefore it is regarded as an 'objective' approach of determining weights (Zeleny, 1982).

- Step 1: determine the normalised criteria scores using a weighted sum method.
- Step 2: determine the entropy E_i, $0 \le E_i \le 1$, for each criterion:

$$E_i = -k\sum_i x_{ij} log(x_{ij}) \qquad \text{B-2}$$

where k is a constant $k = 1/\log(m)$, m is the number of alternatives and.

- Step 3: determine the measure of dispersion which is the complement of entropy

$$D_i = 1 - E_i \qquad \text{B-3}$$

- Step 3: normalise the sum of the weights

$$w_i = \frac{D_i}{\sum D_i} \qquad \text{B-4}$$

B2.5 Trade-off

The trade-off method is rooted in the utility theory formalised by Keeney and Raiffa (1976). The basic idea is to compare two hypothetical alternatives with respect to two criteria while the other remaining criteria are considered to be equal for both alternatives. The DM is asked how much of one criterion he or she is willing to give up, in order to obtain a state improvement of the other criterion. A typical question using this method is to find out which option is preferred by the DM, (a) option A with criterion *i* at its best value and criterion *j* at its worst value, (b) option B with criterion *i* at its worst value and criterion *j* at its best value. By choosing which option the DM prefers, the more important criterion is identified. This questioning process is repeated with different stated levels of improvement or worsening the criteria until the DM thinks that the two options are indifferent. This indifference point is an indication of the judgement ratio between the two criteria.

Given a decision problem with a set of criteria $c_1, c_2, \ldots, c_n$, where n is at least 2 and x be a set of criteria scores $x_1, x_2, \ldots., x_n$ a value trade-off can be elicited by determining two alternatives A_1, A_2 that differ in terms of two criteria (x_1, x_2) assuming all the other criteria scores are held fixed. Alternative A_1 is characterised by (x_a, x_d) representing the specific achievement of (x_1, x_2). Similarly, A_2 is characterised by (x_b, x_c). To specify a value trade-off, let's assume that the two alternatives A_1, A_2 are indifferent to each other. There are four interpretations of the value trade-off, which are also graphically illustrated in Figure B.2:

1. From (x_a, x_d), an increase in x_1 to x_b is compensated by a decrease in x_2 to x_c.
2. From (x_b, x_c), an increase in x_2 to x_d is compensated by a decrease in x_1 to x_a.
3. From (x_a, x_c), an increase in x_1 to x_b and an increase in x_2 to x_d are equally valued.
4. From (x_b, x_d), a decrease in x_1 to x_a and a decrease in x_2 to x_c are equally valued.

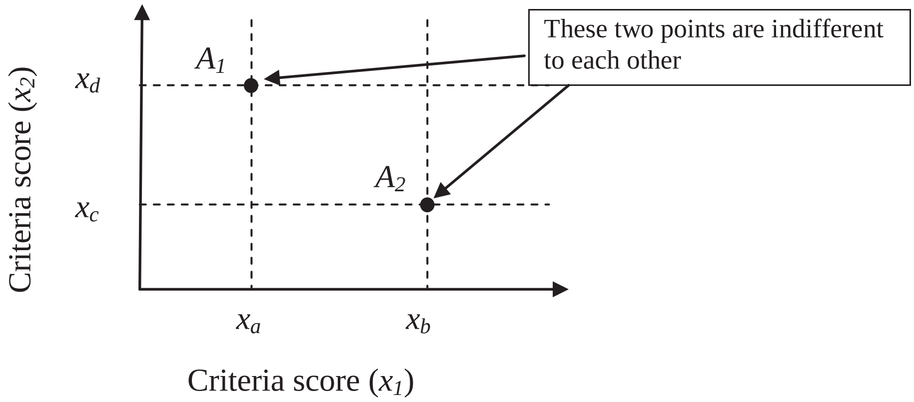


Figure B.2 Visual interpretation of value trade-offs (adapted from Keeney (2002))

Using this model, trade-offs between two criteria can be determined by questioning the DMs the amount of decrease or sacrifices the DM is willing to accept for a very specific amount of increase in other criteria. Such a questioning model can be captured as follows:

Indicate the amount for an increase or decrease in criterion x_2 that are equivalent to each of an unit increase in criterion x_1

A problem with this method is that most people do not give their judgement without referencing to the actual implication of the trade-offs. This method can be difficult to apply and the results can be inconsistent (Hobbs, 1980).

B2.6 Pair-wise comparison

The pairwise comparison technique involves comparing each criterion against other criterion in pairs. For a problem with n criteria, n(n-1)/2 comparisons are required. The method was first proposed by Klee (1971) but the most well-known use of this method is Saaty's Analytic Hierarchy Process (AHP). The procedure begins with comparing each pair of criteria on a nine-point scale as described in the AHP in Appendix A1.2. The nine-point scale reflects the relative importance of criterion *i* to criterion *j*. The ratings (from the 9 point scale) are placed in a pairwise comparison matrix (a square matrix of dimension *n*). Each column or row is a vector of weights associated with the corresponding criterion. The eigenvalues are calculated to represent the corresponding criteria weights. An advantage of this method is that the DM is required to consider two criteria at time, instead of considering multiple criteria. A critique of this method, the problem of rank reversal, is detailed in Appendix A1.2, the AHP method.

B2.7 Value tree weights

If the decision problem is structured as a value tree (a multi-level hierarchy of criteria), weights are typically assigned to different levels of the tree. The two types are :

- *Relative weight* – the weights are assigned within the families of criteria in which the criteria all share the same parent criterion. The weights within the family are typically normalised to unity (e.g. 1 or 100).
- *Cumulative weight* – the product between the relative weight of a criterion within the family and the relative weight of the parent criterion. The sum of all cumulative weights (across all families of criteria) should be unity (e.g. 1 or 100). The relative weight of a primary criterion is the sum of the cumulative weights of all its secondary criteria.

There are two approaches to assess the relative weights of each criterion:

- *Top-down* – works from the top of the value tree to the bottom. It consider first the relative importance of all the major families of criteria (primary criteria), and then the criteria within the primary criteria (secondary criteria) .
- *Bottom-up* – works from the bottom of the value tree to the top. It beings by assessing relative weights within each primary criterion and then assess across the primary criteria. The approach is more appropriate for decision problems with large number of criteria to work with.

B2.8 Distance to goal

The normalised criteria score is measured based on the distance away from an ideal target. This technique involves the assignment of an ideal target (*t*) that is an achievement of a criterion that DM would like to realise:

- If a raw criterion score has a performance less than the target $x^* < t$:

$$x = \frac{x^*}{d}$$

- If a raw criterion score has a performance greater than the target $x^* > t$:

$$x = \frac{d}{x^*}$$

Appendix C. Review of Journal Articles on MCDA

C1 Summary of review papers on MCDA

Citation	Decision context	Method
Romero and Rehman (1987)	Natural resources management	Review 150 applications of the Multi-criteria decision analysis (MCDA) problems to the management of fisheries, agricultural land use, forestry and water resource
White (1990)	General	Provides a bibliography on applications of multiple-objective methods which use no a priori explicit value function and are complex enough to require mathematical programming aids. The survey covers the period 1955-86.
Corner and Kirkwood (1991)	General	Provide a survey of applications of decision analysis published from 1970 through 1989. Five areas of application were surveyed: energy, manufacturing and services, medical, public policy, and general
Keefer *et al.* (2004)	General	Provide perspective on, trends and developments in decision analysis applications, based primarily on an exhaustive survey of decision analysis applications published in the period 1990-2001.
Mendoza and Martins (2006)	Forest and other natural resource management.	Review traditional MCDA techniques and describes new modelling approaches to forest management. It also describes new MCDA paradigms aimed at addressing the inherent complexity of managing forest ecosystems and critically analyse the limitations of traditional models
Vaidya and Kumar (2006)	General	Review a 150 application papers that used AHP (Analytical Hierarchy Process), a MCDA method
Hajkowicz and Collins (2007)	Water management	Review 113 published water management MCDA studies from 34 countries
Lai *et al.* (2008)	Water management	Review MCDA techniques with respect to urban water management and compare to other integrative approaches such as the cost-benefit analysis, triple bottom line and integrated assessment
Ananda and Herath (2009)	Forest management	Review application of MCDA techniques to forest management and planning with a focus on highlighting theoretical underpinnings and controversies.
Sadok *et al.* (2009)	Cropping system management	Review MCDA techniques with the specificities of ex ante sustainability assessment of alternative cropping systems.
Wang *et al.* (2009)	Energy management	Review MCDA techniques and criteria with respect to sustainable energy management.
Ho *et al.* (2010)	Supply chain management	Review published articles from 2000 to 2008 on MCDA approaches for supplier evaluation and selection.
Ho (2008)	General	Reviews articles on integrated AHP which appeared in the international journals from 1997 to 2006

C2 Summary of MCDA applications in the field of water resources management

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Keeney and Wood, 1977)	MAUT	Water resources development plans for the Tisza River basin in Hungary.	5 alternatives 12 criteria 1 DM(s)	Scaling factors (trade-off)	Utility function using mid-point technique Qualitative: 0 – 100 scale Quantitative: numerical (From a previous study)	Problem structuring had been conducted by the Hungarian National Water Authority planners	Sensitivity analysis: change criteria weights	Preferential independence
(Gershon *et al.*, 1982)	ELECTRE I ELECTRE II	Assess impact of alternative river basin development strategies for the Santa Cruz River in the vicinity of Tucson, Arizona	25 alternatives 13 criteria 1 DM(s)		Qualitative: 5 tier scale Quantitative: numerical (Method unknown)	Cost effectiveness approach (Duckstein and Opricovic, 1980)	Sensitivity analysis: change criteria score interval and apply equal weights	Preferential independence
(Onta and Das Gupta, 1991)	CP	Planning problem involving integrated use of surface and ground water in the Bagmati River Basin, Nepal	6 alternatives 6 criteria 1 DM(s)	(Method Unknown)	(Obtained from simulated dynamic models)	Formulated based on the simulated dynamic models	Sensitivity analysis: study the changes to criteria weights/scores for the optimal option	Preferential independence
(Rios Insua and French, 1991)	SAW	Flood-plain management in Dallas, Texas.	8 alternatives 10 criteria 1 DM(s)	Direct weighting	Numerical (Method unknown)	From a previous paper		Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Bárdossy and Duckstein, 1992)	Fuzzy CP	Regional management of a karstic aquifer in Hungary	6 alternatives 6 criteria 1 DM	Fuzzy (Determine distance between each alternative and an ideal point)		Pre-determined method unknown		Preferential independence
(Ridgley and Rijsberman, 1994)	AHP	Evaluate alternative management policies for the freshwater system in Haringvliet in the Rhine delta	7 alternatives 17 criteria Multiple DM	Eigenvector (pairwise comparison)	Criteria scores: qualitative - interval scale Quantitative – monetary (Method Unknown	Through stakeholder engagement managed by the consultative committee Construct value tree	Sensitivity analysis: observe options' rankings to changes in the judgement ratio	Preferential independence
(Abu-Taleba and Mareschal, 1995)	PROMETHEE V	Water resource planning in Jordan	29 alternatives 18 criteria	(Normalised weighting determined from previous publication)	(Pairwise comparison to determine preference function)	From a previous paper	Sensitivity analysis: change criteria weights	Preferential independence
(Stewart and Scott, 1995)	SAW	Regional water resource planning in South Africa	5 alternatives 4 criteria Multiple DM	Direct assignment (Random weights	Numerical (Utility function using quadratic approximation)	Scenario planning	Apply random weights to find the alternative with the maximum value for each set	Preferential independence
(Anand Raj, 1995)	ELECTRE I ELECTRE II	Water resources planning Krishna River basin, South India	27 alternatives 6 criteria DM	(Method Unknown)	Numerical (From previous study)	Unknown	Sensitivity analysis: change threshold values	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Anand Raja and Kumarb, 1996)	ELECTRE I ELECTRE II	Water resources planning Krishna River basin, South India	24 alternatives 18 criteria N/A DM	(Method Unknown)	Numerical (From previous study)	Unknown	Sensitivity analysis: change threshold values	Preferential independence
(Netto *et al.*, 1996)	ELCTRE III	Plan for augmenting water resources in the Adour-Garonne Basin (southwestern France)	8 alternatives 13 criteria N/A DM	Qualitative: 4 tier scale	Qualitative: 1 – 10 scale Quantitative: numerical (Method unknown)	Discussion between representatives from different stakeholder groups		
(Offringa and de Wet, 1996)	SMART		N/A alternatives 55 criteria N/A DM	Swing and judgement ratio	Quantitative: 0 – 100 scale (Method Unknown)			
(Al-Kloub *et al.*, 1997)	PROMETHEE	Rank major water projects in Jordan	72 alternatives 24 criteria N/A DM	Group workshop to identify cause-effect relationship for value tree	(Pairwise comparison)	Value focused thinking + Nominal Group Technique	Sensitivity analysis: change criteria weights	Preferential independence
(Al-Shemmeri *et al.*, 1997)	PROMETHEE	Water resource planning in Jordan	72 alternatives 24 criteria N/A DM	Group workshop to identify cause-effect relationship for value tree	(Pairwise comparison)	Value focused thinking + Nominal Group Technique	Sensitivity analysis: change criteria weights	Preferential independence
(Tkach and Simonovic, 1997)	CP + Geographical Information System (GIS)	Floodplain management for the Red River Valley, Canada	4 alternatives 3 criteria N/A DM	0 – 1 points (Direct assignment based on literature)	(From other models)	Unknown	3 sets of weights were proposed	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Martin *et al.*, 1999)	PROMETHEE + GIS	Development of Saint Charles River, Canada	8 alternatives 11 criteria 12 DM	0 – 100 points (Direct assignment of 0 – 100 points or Simos (1990) card method)	(From other models (GIS))	Decision group of 12 members met 5 times over a period of 8 months	Graphical projection of scenario performances	Preferential independence
(Rajabi *et al.*, 1999)	GP	Water supply planning for Regional Municipality of Waterloo, Canada	12 alternatives 7 criteria N/A DM	(Distance to goal)	Expert judgement		Not addressed	Preferential dependence
(Raju and Pillai, 1999)	AHP, ELECTRE, PROMETHEE, CP	Selection of reservoir configuration for Chaliyar river basin, Kerala, India	8 alternatives 6 criteria 1 DM	Weighting methods as per respective MCDA methods	0 – 100 points or 2 tier qualitative scale Average + Good (Expert judgement and available data)	Discussion with a senior officer who act as a DM	Sensitivity analysis	Preferential independence
(Bender and Simonovic, 2000)	Fuzzy CP	Comparing water resource systems for the Tisza River basin in Hungary	5 alternatives 12 criteria N/A DM	Fuzzy (Determine distance between each alternative and an ideal point)	(From previous study)	Unknown	Fuzzy criteria weights and criteria scores	Preferential independence
(De Marchi *et al.*, 2000)	NAIADE	Water resource issues in Troina, Sicily	7 alternatives 8 criteria	Direct ranking of alternative with respect to each criterion	Construction of qualitative functions	Institutional analysis + survey	Not addressed	Preferential independence
(Flug *et al.*, 2000)	MAVT	Evaluation of water resources plan for the Glen Canyon Dam, Colorado River, Arizona, USA	9 alternatives 7 criteria N/A DM	3 sets of weight: Direct assignment by an expert; equal weights; survey	Construction of qualitative functions	Public consultation	Sensitivity analysis: change criteria weights	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Jaber and Mohsen, 2001)	AHP	Evaluation of alternative water resource supply in Jordan	4 alternatives 5 criteria N/A DM	Eigenvector (pairwise comparison)	Pairwise comparison of alternatives	Unknown	Not addressed	Preferential independence
(Kheireldin and Fahmy, 2001)	CP	Long-term water strategies evaluation for Egypt	4 alternatives 14 criteria N/A DM	0 – 100 points (Direct assignment)	From simulation models (normalised by interval scale property method)	Unknown	Sensitivity analysis: change criteria weights with 6 sets of weights	Preferential independence
(Lamy *et al.*, 2002)	MAVT RESTORE (GIS based decision model)	Evaluation of watershed restoration strategies	20 alternatives 28 criteria Multiple DM	0 – 1 points (Direct assignment)	From RESTORE (GIS) model	Public consultation and stakeholder engagement activities organised by watershed council	Not addressed	Preferential independence
(Mahmoud *et al.*, 2002)	MAUT + GIS	Sitting and sizing of desalination facilities in Egypt	13 alternatives 3 criteria 1 DM	Unknown	From GIS model	Unknown	Not addressed	Preferential independence
(Sharifi and Rodriguez, 2002)	MAUT and ELECTRE	Rehabilitation of ground water resources in Aquifer 23, La Mancha, Spain	10 alternatives 4 criteria N/A DM	0 – 100 points (Direct assignment) and Eigenvector (Pairwise comparison)	From other models (water balance models + GIS) Normalised by raw-max and interval method	Decision support framework	Sensitivity analysis: change criteria weights	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Joubert *et al.*, 2003)	MAVT	Evaluate water supply and demand problems for Cape Town	23 alternatives 19 criteria Multiple DM	Swing weight	For qualitative scores (0 – 100 points); For quantitative scores (piecewise linear interpolation)	Initial problem structuring and specialist workshops	Sensitivity analysis: change criteria weights	Preferential independence
(Prato, 2003)	MAUT	Evaluate management options for Missouri River	10 alternatives 5 criteria N/A DM	Percentage deviation from the ideal performance level	4 sets of numerical (Value tree weight + direct assignment)	Unknown (Evaluated by U.S. Army Corps of Engineers)	4 sets of weights were used which can interpreted as sensitivity analysis	Preferential independence
(Simon *et al.*, 2004)	PROMETHEE, Hasse Diagram Technique	Selection of water management strategies for the cities of Berlin and Potsdam	9 alternatives 4 criteria N/A DM	Pairwise comparison	(From simulation models)	Unknown	Not addressed	Preferential independence
(Srdjevic *et al.*, 2004)	TOPSIS	Select reservoir operating system	12 alternatives 18 criteria	Entropy	(From simulation models)	Unknown	Sensitivity analysis: compare with 2 other MCDA method (modified TOPSIS and CP)	Preferential independence
(Abrishamchi *et al.*, 2005)	CP	Urban water supply management in Zahian, Iran	8 alternatives 9 criteria 2 DM	Direct assignment within a value tree	Construction of a qualitative function (5 tier)	Unknown	Sensitivity analysis: change criteria weights and criteria scores	Preferential independence
(Hajeeh and Al-Othman, 2005)	AHP	Selection desalination technologies	4 alternatives 7 criteria Multiple DM	Eigenvector (Pairwise comparison)	Unknown	Unknown	Not addressed	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Rossi *et al.*, 2005)	NAIDE	Assessment of drought mitigation strategies	8 alternatives 12 criteria 5 DM	Direct assignment (9 tier ordinal scale)	Construction of a qualitative function (9 tier); Numerical for quantitative criteria from simulation models	Unknown	Use of qualitative assessment of weights and criteria scores	Preferential independence
(Morais and Almeida, 2006)	ELECTRE	Selection of city for proving water supply system in Brazil	8 alternatives 4 criteria	Direct assignment (1 – 5 points)	Construction of a qualitative function (0 – 1 point); Numerical for quantitative criteria	Decision support framework; stakeholder engagement	Sensitivity analysis: change criteria weights	Preferential independence
(Pietersen, 2006)	MAVT	Management of groundwater resources in South Africa	2 alternatives 8 criteria Multiple DM	Interval SMART/Swing method	(From previous study)	Decision support framework; public consultation, workshops with DMs	Not addressed	Preferential independence
(Lai *et al.*, 2007)	Fuzzy inference system	Selection cases with different volume and application of recycled greywater and rainwater in a household	4 alternatives 4 criteria 1 DM	Fuzzy IF-THEN rule (pairwise comparison)	Normalised into fuzzy criteria scores (From simulation models)	Unknown	Use of fuzzy criteria scores	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Makropoulos *et al*., 2007)	SAW/OWA + GIS	Site selection for wastewater treatment facilities	2 alternatives 9 criteria N/A DM	Direct assignment (1 – 5 points)	Fuzzy IF-THEN rule to standardise (From simulation model)	WAND decision support framework	Use of fuzzy inference system to standardise criteria scores	Preferential independence
(Dong *et al.*, 2008)	AHP, Fuzzy	Assessment of urban drainage system in Shenzhen city, China	2 alternatives 8 criteria N/A DM	Eigenvector (pairwise comparison)	From simulation models	Unknown (discussion with stakeholder)	Use of fuzzy numbers	Preferential independence
(Srdjevic and Medeiros, 2008)	Fuzzy AHP	Assessment of water management plans in part of the Paraguacu River Basin in Brazil	3 alternatives 24 criteria	Fuzzy Saaty's 1 – 9 point judgement	Unknown	Unknown	Use of fuzzy weights	Preferential independence
(Chowdhury and Zaman, 2009)	SAW	Selection of the optimal alternative: rehabilitation of a regional drainage channel in Bangladesh	3 alternatives 10 criteria 72 DM	Direct assignment	Construction of a qualitative scale; Numerical for quantitative scores (normalised based on difference between max and min scores)	Public consultation through interview	Sensitivity analysis: change weights	Preferential independence
(Alipour *et al.*, 2010)	Fuzzy MAUT	Evaluation of site location for diversion of water into Lake Urmia, Iran	5 alternatives 8 criteria N/A DM	Unknown (fuzzy numbers)	Construction of a qualitative function (fuzzy numbers)	Unknown	Use of fuzzy criteria scores and fuzzy criteria weights	Preferential independence

Citation	MCDA method(s)	Decision context	Problem Size	Criteria weights (method)	Criteria scores (method)	Problem structuring	Judgement uncertainty	Criteria interaction
(Calizaya *et al.*, 2010)	AHP	Integrated water resources management in the Lake Poopo Basin, Bolivia	7 alternatives 10 criteria 8 DM	Eigenvector (Pairwise comparison)	Unknown	Unknown	Sensitivity analysis: change consistency ratio	Preferential independence
(Joerin *et al.*, 2010)	MACBETH	Vulnerability assessment of drinking water utilities	28 alternatives 4 main criteria 3 DM	Swing interval method in a pairwise comparison fashion	Construction of a qualitative function (From Questionnaire / database / observation)	Expert panel	Sensitivity analysis:	Preferential independence
(Weng *et al.*, 2010)	MODM	Water resources management in the Haihe River Basin.	5 criteria 10 criteria	Distance to target	From simulation models	Integrated scenario based multi-criteria DSS	Use of fuzzy MCDA	Preferential independence
(Urrutiaguer *et al.*, 2010)	SAW	Selection of Water Urban Sensitive Design for Melbourne, Australia	1 alternative 9 criteria Multiple DM	Value tree weighting	(From simulation models)	Unknown (structured by Melbourne Water with Steering Committee)	Not addressed	Preferential independence
(Garfì *et al.*, 2011)	AHP	Strategic environmental assessment of safe water supply in Brazil	8 alternatives 23 criteria N/A DM	Eigenvector (pairwise comparison)	(From other studies)	Strategic Environmental Assessment (SEA); discussion with stakeholder groups	Not addressed	Preferential independence

Appendix D. Fuzzy Set Theory and Choquet Integral

D1 Fuzzy set theory

A set is a collection of distinct objects which share the same characteristics defined on a universe[28] *X*. The individual elements in the universe *X* can be denoted as *x*. A set's conventional binary logic is represented mathematically by the following function:

$$\chi_A(x) = \begin{cases} 1, & x \in A \\ 0, & x \notin A \end{cases}$$

where $\chi_A(x)$ is the membership of element *x* within the set *A*. *Membership* of a class can be interpreted as the degree of belongingness to a class (e.g. on a scale of 0–1, what is the membership degree for a person with a height of 170cm to be classified as tall?).

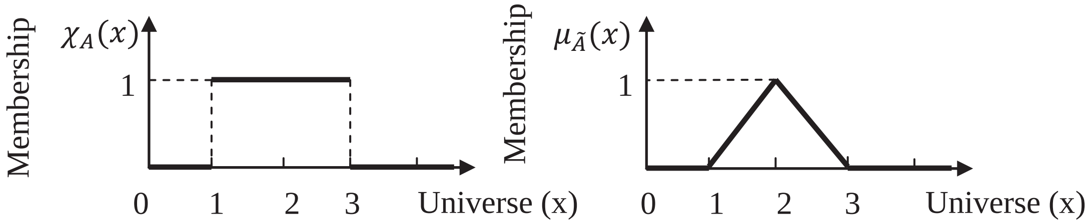
A normal set is referred to as a crisp set (non-fuzzy). In the classical binary set theory, an element either belongs to a class or it does not. The transition for an element in the universe between classes (membership and non-membership) is abrupt and well-defined. There is no overlapping of membership between two classes of object. A set that is classified under the classical binary set is referred to as a *crisp* set.

The fuzzy set, introduced by Zadeh (1965), is an alternative to the conventional notion of a set by describing a set using degree of membership. A fuzzy set is a set that contains elements having varying degrees of membership or varying degrees of belongingness to a class. The notion of a fuzzy set is a set $\tilde{A}$ of the universe of *X* that is characterised by the *degree of membership* $\mu_{\tilde{A}}(x)$, indicated by values in the range [0, 1], with 0.0 representing no membership and 1.0 representing absolute membership. In other words, $\mu_{\underline{A}}(x)$ is a value on the unit interval that measures the degree to which element *x* belongs to the fuzzy set $\tilde{A}$. A letter with a tilde (˜) on top is used to denote a fuzzy set. A fuzzy set $\tilde{A}$ is usually denoted by the set of pairs:

$$\tilde{A} = \left(x, \mu_{\tilde{A}}(x)\right), x \in X$$

[28] A universe is a class that contains all objects that one wishes to consider in a given situation.

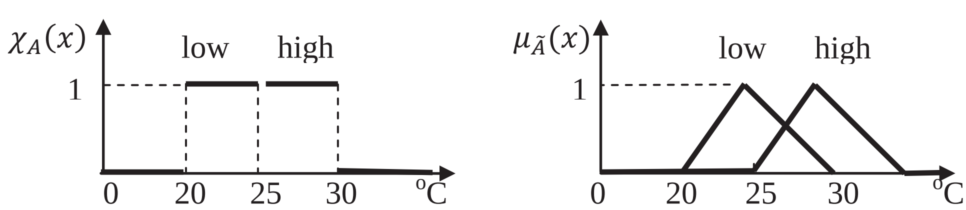
Therefore, $\mu_{\tilde{A}}(x)$ is a value on the unit interval that measures the degree to which element *x* belongs to the fuzzy set Ã. Similarly, $\chi_A(x)$ is value on the unit interval that measures the degree to which element *x* belongs to the crisp set *A*. An example of a crisp set (i.e. conventional set) *A* and a fuzzy set $\tilde{A}$ defined over the interval $x \in [1,3]$ in the universe of *X* is shown in Figure D1.



(a) (b)

Figure D.1 Example of (a) crisp set A and (b) fuzzy set ? (Ross, 2004)

One key difference between a crisp set and a fuzzy set is that, in a fuzzy set there is no sharp boundary between those elements that belong to the class and those that do not. For example in a crisp set, a set of low temperature (20^{o}C–24 ^{o}C) cannot overlap with a set of high temperature (25^{o}C–30 ^{o}C). On the contrary in the real world situation, the sets of high and low temperature are relative values and can overlap with one another (Figure D.2). This kind of logic does not follow the precepts of classical binary logic.



(a) (b)

Figure D.2 No overlapping between (a) crisp sets but overlapping is allowed between (b) fuzzy sets

To apply fuzzy sets to model information and apply arithmetic operators on them, fuzzy numbers are used. Fuzzy numbers are fuzzy sets described by membership functions, characterised by a given interval of real numbers associated with a grade of membership. There are two common types of fuzzy numbers, trapezoidal fuzzy numbers (TrFN) and triangular fuzzy number (TFN) in which TFN is a special case of TrFN (Figure D.3). TrFN can be defined by the fuzzy set $\tilde{B}$ with four real numbers (b_1, b_2, b_3, b_4). Let TFN be defined by the fuzzy set $\tilde{A}$ (0, a_1, a_2, a_3) and TFN and TrFN membership functions are expressed by Eqn D-1 and Eqn D-2 respectively.

$$\mu_{\tilde{A}} = \begin{cases} 0, & x \le a_1 \\ \dfrac{x-a_1}{a_2-a_1}, & a_1 \le x \le a_2 \\ \dfrac{a_3-x}{a_3-a_2}, & a_2 \le x \le a_3 \\ 0, & x \ge a_3. \end{cases} \qquad \textbf{D-1}$$

$$\mu_{\tilde{B}} = \begin{cases} 0, & x \le b_1 \\ \dfrac{x-b_1}{b_2-b_1} & b_1 \le x \le b_2 \\ 1 & b_2 \le x \le b_3 \\ \dfrac{b_4-x}{b_4-b_3}, & b_3 \le x \le b_4 \\ 0, & x \ge b_4. \end{cases} \qquad \textbf{D-2}$$

Another form of notation for the fuzzy number $(\tilde{A})$ is as follows:

$$\tilde{A} = \left\{ \frac{\mu_{\tilde{A}}(x_1)}{x_1} + \frac{\mu_{\tilde{A}}(x_2)}{x_2} + \cdots + \frac{\mu_{\tilde{A}}(x_i)}{x_i} + \cdots \right\}$$

where $\mu_{\tilde{A}}(x_i)$ is the membership degree at x_1.

These two fuzzy numbers can be defined by using a shorter convention:
$[0, a_1, a_2, a_3]$ for TFN; and $[b_1, b_2, b_3, b_4]$ for TrFN respectively.

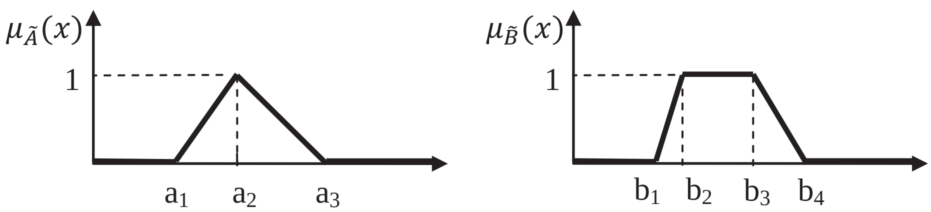


Figure D.3 (a) Triangular and (b) Trapezoidal fuzzy numbers

This alternative logic provides a way of dealing with problems with vague or overlapping set membership (Zadeh, 1965). Fuzzy set theory has had the greatest success in consumer product control applications. The application has extended to MCDA and formed a new field called fuzzy multi-criteria decision aid (FMCDA) (Bellman and Zadeh, 1970; Chen and Hwang, 1992; Fodor and Roubens, 1994; Carlsson and Fuller, 1996; Ribeiro, 1996).

D1.1 Fuzzy multi-criteria decision aid (FMCDA)

As mentioned earlier in Section 2.4.2 p.34, all MCDA methods differ by their DSM. This same classification applies to FMCDA. The DSM in FMCDA can be divided into two phases (Dubois and Prade, 1980; Zimmermann, 1987; Chen and Hwang, 1992):

1. *Fuzzy rating* – the aggregation of performance scores for all criteria. The performance scores in FMCDA can be expressed as fuzzy numbers which require a different treatment to aggregate.
2. *Fuzzy ranking* – in MCDA, the ranking order of alternatives is easy to obtain because the final performance scores for alternatives are in numerical numbers. In FMCDA, to obtain the final ranking order of alternatives is not a simple task because the performance scores for alternatives with respect to all criteria may be expressed by fuzzy numbers. There is a range of fuzzy ranking methods to compare fuzzy numbers.

D1.2 Fuzzy rating methods in MADA

As the name FMCDA suggests, the theory of fuzzy set is applied to different methods of MCDA. Thus, the number of FMCDA methods available is almost equivalent to the number of MCDA methods. In order not to exhaust the reader with the vast amount of FMCDA literature, the author limits the review to MADA which is the stream that this research has focused on (justification is provided in Section 2.4.3 p.35). The following, summarise the two main groups of FMCDA approach in MADA (Figure D.4):

1. Fuzzy simple additive weighting (FSAW)
2. Fuzzy analytic hierarchy aggregation (FAHP).

Fuzzified versions of other MCDA approaches, such as goal programming are available, but since the focus of this research is on the MADA branch and not on the MODA branch, the reader interested in further information is referred to Chen and Hwang

(1992). Justification for the selection of a MCDA method is provided in Section 2.4.3 p.35.

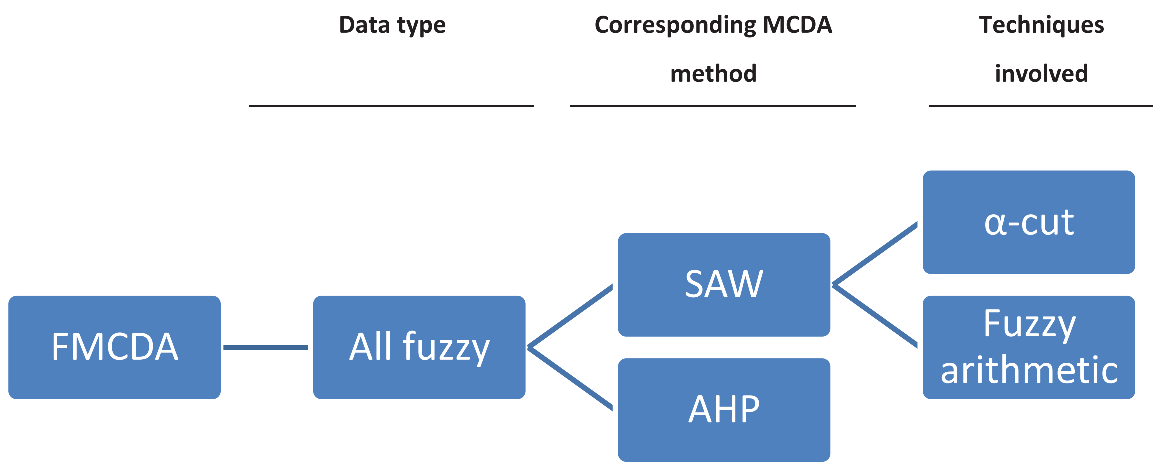


Figure D.4 Classification of FMCDA methods

A. Fuzzy simple additive weighting

The classical simple additive weighting method is a decision problem D defined as follows:

$$D = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

$$w = (w_1, w_2, \cdots, w_n)$$

where

$X = ((x_i, w_i) \mid \mathrm{i} = 1, 2, \dots, n)$ is a set of criteria and their associated weights w_i

$x = \left((x_{ij}) \mid \mathrm{i} = 1, 2, \dots, n; j = 1,2, \dots, m\right)$ is the performance score for alternative A with respect to criterion x_i

A = (a_j | j = 1, 2, …, m) is a set of alternatives.

The classical MCDA method assumes all x_{ij}, w_j values to be crisp numbers. The performance for each alternative (z_i) is calculated by Eqn D-3:

$$z_j = \sum_{i=1}^{n} w_i x_{ij} \qquad \text{D-3}$$

The selection of preferred alternative A^* is based on the maximum performance score for the alternative, z_i. In FMCDA, the performance rating for x_{ij} can be either crisp, fuzzy numbers and/or linguistic. To extend fuzzy set to this method, both w_i and x_{ij} are defined as fuzzy numbers:

$$\widetilde{w}_i = \{w_i, \mu_{\widetilde{w}_i}(w_i)\}, \forall i$$

$$\tilde{x}_{ij} = \{x_{ij}, \mu_{\tilde{x}_{ij}}(x_{ij})\}, \forall i, j$$

where w_i and x_{ij} are real numbers but $\mu_{\widetilde{w}_i}(w_i)$ and $\mu_{\tilde{x}_{ij}}(x_{ij})$ are membership values in the range [0,1]. The performance score for alternative A_i is described as:

$$\tilde{z}_j = \{z_j, \mu_{\tilde{z}_j}(z_j)\}, \forall j$$

To approximate $\mu_{\tilde{z}_j}(z_j)$ there are two main approaches:

1. ***α-cut method***

Baas and Kwakernaak's (1977) method is one of the first that applied the α-cut method to obtain the membership function $\mu_{\tilde{z}_j}(z_j)$. There are other subsequent modifications based on this approach, including that of Kwakernaak (1979), Chen and McInnis's (1980) and Dubois and Prade's (1982). The following describes Baas and Kwakernaak's approach which involves very tedious steps:

Step 1: Set an initial α value for $\mu_{\tilde{z}_j}(z_j)$, say α_0.

Step 2: Determine the corresponding w_i and x_{ij} values in the fuzzy numbers $\widetilde{w}_i$ and $\tilde{x}_{ij}$ that correspond to the membership degree at α_0 level (Figure D.5).

$$\mu_{\widetilde{w}_i}(w_i) = \mu_{\tilde{x}_{ij}}(x_{ij}) = \alpha_0$$

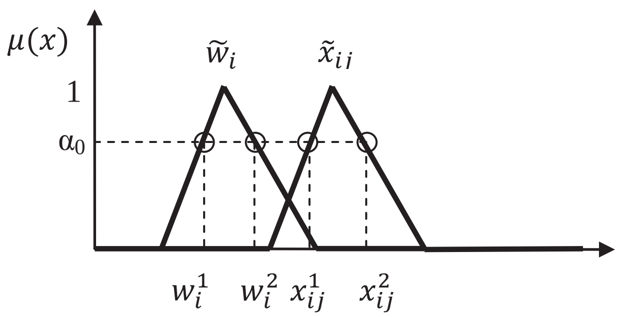


Figure D.5 α0 level and the corresponding *w_i* and *x_{ij}* values

Step 3: Determine the possible z_i values with $\mu_{\tilde{z}_j}(z_j)$ that correspond to α_0 (refer to). Calculate the corresponding z_j for the identified $(w_i^1, w_i^2, x_{ij}^1, x_{ij}^2)$ values using the Eqn 2-4. In the case where there are two criteria and two weights, then there will be

16 possible combination of $w_i^1, w_i^2, x_{ij}^1, x_{ij}^2$ (i.e. $2^4 = 16$). The number of possible values for z_i hence increases dramatically with the number of the criteria considered.

Step 4: Select the max and min value of all the possible zj values to be z_j^1, z_j^2.

Step 5: Repeat the process from step 1 by choosing another α level. This is done to obtain z_j^1, z_j^2 at other α levels. The greater the number of iterations, the closer it is to approximate the real $\tilde{z}_j$.

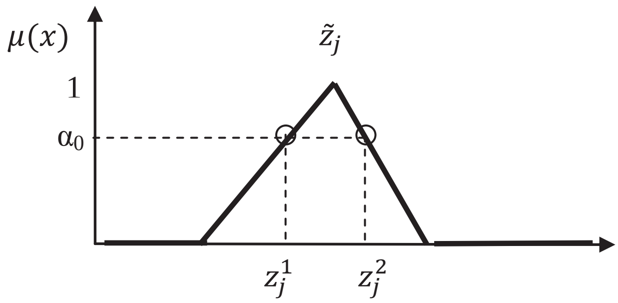


Figure D.6 α0 level and the corresponding z_j values

Step 6: The ranking of $\tilde{z}_j$ can be done by observation or by using any proper ranking methods as described in the Section D1.3 p.300.

2. *Fuzzy arithmetic*

Bonissone (1979) offered a simpler approach compared to the α-cut method by applying fuzzy arithmetic to calculate the fuzzy performance score for each alternative. The method assumes that the weight and criteria ratings can be approximated by TrFN. Let $\tilde{A}$ and $\tilde{B}$ be defined as (a_1, a_2, a_3, a_4) and (b_1, b_2, b_3, b_4) respectively. The simple additive model using Eqn D-3 is computed by applying the following fuzzy arithmetic operations:

$$\tilde{A}(+)\tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4) \quad \textbf{D-4}$$

$$\tilde{A}(\cdot)\tilde{B} = (a_1 b_1, a_2 b_2, a_1 b_3 + b_1 a_3 - a_3 b_3, a_2 b_4 + b_2 a_4 - a_4 b_4) \quad \textbf{D-5}$$

Note that the fuzzy arithmetic operators are denoted by the normal operators in () and also that Eqn D-5 is an approximate in that the left and right spreads of the calculated results are not exact, but it introduces very little error. By applying Eqns D-4 and D-5, Eqn D-3 becomes:

$$\tilde{z}_j = \{\tilde{w}_1(\cdot)\tilde{x}_{1j}\}(+)\{\tilde{w}_2(\cdot)\tilde{x}_{2j}\}(+)\cdots(+)\{\tilde{w}_n(\cdot)\tilde{x}_{nj}\} \quad \textbf{D-6}$$

The ranking of $\tilde{z}_j$ can be done by observation or by using any proper ranking methods as described in the Section D1.3 p.300.

Baas and Kwakernaak's α-cut method takes a trial and error approach by estimating different α values to derive the membership function for $\tilde{z}_j$. There are modifications to Baas and Kwakernaak's α cut method, which improve the search efficiency by not undertaking the trial and error approach and also expand the application to solve more than two criteria problems. The α-cut approach is still a complex way of obtaining the fuzzy performance scores for alternatives.

Bonissone's (1979) fuzzy arithmetic operations use the extension principle. Each fuzzy set is associated with a linguistic term. This approach is applicable only when fuzzy concepts are represented by TFN or TrFN. The first four methods involve complex computation of the final fuzzy utility.

B. Fuzzy analytical hierarchy aggregation

This group deals with the fuzzy version of Saaty's (1980) AHP. In the classical AHP, the DM has to provide ratios (a_{ij}) for each pairwise comparison between alternatives $\{A_1, A_2, \ldots, A_n\}$ for each criterion in a hierarchy. The ratio (a_{ij}) represents the relative importance of A_i over A_j, for example, such as 1/3 or 1/5, taken from the set (1, 3, 5, 9). The ratios make up a pairwise comparison matrix for each criterion. Refer to Section A1.2 p.262 for the classic AHP approach.

Larrhoven and Pedrycz (1983) extended AHP by transforming a_{ij} into fuzzy numbers. The fuzzy numbers represent linguistic expressions such as 'approximately 1 to 3'. The main problem is to compute the corresponding fuzzy performance scores. There are many ways in the classical AHP to obtain the performance score (x_{ij}) of alternative A_i and the weights (w_i). The most popular method being the eigenvector method as discussed in Section A1.2 p.262. Larrhoven and Pedrycz (1983) proposed to use the logarithmic least square method to obtain the fuzzy performance score $\tilde{x}_{ij}$ and the fuzzy weights $\widetilde{w}_i$. The final utility for each alternative (z_i) is derived by applying fuzzy arithmetic operations on the fuzzy numbers $\tilde{x}_{ij}$ and $\widetilde{w}_i$ based on the classical SAW method.

Buckley *et al.* (1999) also extended fuzzy set theory to AHP by representing the comparison ratios as TrFN and applied an evolutionary algorithm to obtain the fuzzy performance scores $\tilde{x}_{ij}$ and fuzzy weights $\widetilde{w}_i$ instead of direct computation of fuzzy eigenvalues and fuzzy eigenvectors. The fuzzy versions of AHP and Saaty's AHP produce very similar results in discriminating among alternatives (Chen and Hwang, 1992). As such fuzzy AHP is a more complicated way of solving an AHP problem.

D1.3 Fuzzy ranking methods

Thus far, the fuzzy rating methods discussed above are concerned with the aggregation of criteria and weights to obtain aggregated fuzzy utilities for alternatives. The next step is to compare the fuzzy utilities using fuzzy ranking methods to obtain ranking order for alternatives. There are more than twenty established fuzzy ranking methods in the literature. In order to provide a concise overview, summary of three popular approaches is presented in the following:

1. *Degree of optimality* – this approach computes a preference score for a fuzzy number and higher the preference score, the more preferred is the fuzzy number. A best fuzzy number is first determined and a preference index for the fuzzy number under consideration is established. The preference score denotes how much better a particular fuzzy number is in relation to other fuzzy numbers. A representative of this approach is that of Baas and Kwakernaak (1977).
2. *Hamming's distance* – this involves the measurement of distance between two ideal solutions (positive and negative). The positive or negative ideal solution consists of the best or worst values for criteria attainable (i.e. $x^- = 0$, $x^+ = 1$). The most preferred alternative has the shortest distance away from the positive ideal solution and the longest distance away from the negative ideal solution. A performance coefficient is then calculated based on the two distances as a comparison for ranking fuzzy numbers. A representative of this approach is that given by Nakamura (1986).
3. *Centroid index* – this methods finds the geometric centre of a fuzzy number, in which each geometric centre can be obtained by Eqn D-7. A representative of this approach is that of Yager:

$$z^* = \frac{\int \mu_{\tilde{z}}(z) \cdot z dz}{\int \mu_{\tilde{z}}(z) dz} \quad \textbf{D-7}$$

Yuan (1991) examined the case where two fuzzy numbers are close to each other, and found that the results obtained by the degree of optimality method cannot distinguish the two fuzzy numbers meaningfully. Under the same situation, the preference scores obtained by the Hamming's distance are shown to be dramatically different. This suggested that the Hamming's distance method is sensitive to minor changes in the fuzzy numbers.

For the centroid index method, each geometric centre only corresponds to *x*, a value only on the horizontal axis. In situations where two fuzzy spread have the same spread (i.e. fuzzy number $\tilde{A} = [a_1\ a_2 a_3]$ and $\tilde{B} = [b_1 b_2 b_3]$ have the same spread if $a_1 = b_1$ and $a_3 = b_3$), the centroid index method cannot distinguish both fuzzy numbers. Variations of this method exist that associate each geometric centre with a y value (vertical axis) such as that of Murakami and Maeda (1984) and Cheng (1998).

Each of these methods is not perfect but the centroid index is by far the most comprehensible in concept among the three approaches and has the ability to measure the relative performance of the decision alternatives in a simple mathematical form.

D1.4 FMCDA in water resources management

The nature of water resource management problems can be generally separated into those of a strategic nature or a tactical nature which involves water system operational issues. Here we focus on reviewing applications of fuzzy MCDA at a strategic level because decision making problems in urban water management are generally concerned at the strategic level involving a high degree of human preference.

A wide range of fuzzy set applications have emerged over the last two decades. Zimmermann (1996) outlined four main categories:

1. *Algorithmic applications* – fuzzy mathematical programming; fuzzy planning methods; fuzzy petri nets; fuzzy clustering etc
2. *Information processing* – fuzzy data bank systems; fuzzy query languages; fuzzy languages etc
3. *Knowledge-based applications* – expert systems; fuzzy control; knowledge based diagnosis etc
4. *Hybrid application areas* – fuzzy data analysis; fuzzy supervisory control etc.

The majority of the applications in water resource management are found in the area of algorithmic applications. This type of application adapts existing MCDA methods to solve problems which involve fuzzy data. The four groups of approach described in section belong to algorithmic application. Generally, the fuzzy set approach compliments the existing MCDA methods by replacing the normal indicator function of a set by a fuzzy set that allows the users to specify what level $x \in A$, expressed by $0 \leq \mu_A(x) \leq 1$.

The application of knowledge-based system models a problem via a system of rules consisting of conditional (IF-THEN) rules and a fuzzy logic inference system. The knowledge-based system describes the relationships between input and output variables. The applications of knowledge-based fuzzy sets in water resource management are reviewed because the method proposed in this thesis also belongs to this application group. Makropoulos *et al.* (2003) developed a spatial decision support system that incorporates fuzzy logic into the strategic planning of site-specific implementation of a particular water management strategy. The model evaluates the sites by comparing the different spatial attributes in the form of geographical information system layers and analysing the suitability using a fuzzy inference system.

Karnib (2004) proposed an approach to evaluate water resource projects' priorities using IF-THEN rules. The performance of each criterion is described as fuzzy sets and a decision rule is based on one criterion (IF criterion 1 is X then priority is Y). A maximum and a minimum fuzzy priority set for each project with respect to each criterion are determined based on the decision rules using the Mamdani inference method (Mamdani and Assilian, 1975). The maximum and minimum fuzzy priority sets are defuzzified to obtain crisp outputs. They are compared to a pre-defined indifference threshold level to determine the partial priority pre-order. The partial relations can show to the DMs which water resources projects are comparable and which are not.

Moving boarder away from water resource planning, Liu (2007) used the IF-THEN approach to evaluate 146 countries' environmental sustainability which includes water quality and quantity evaluation as criteria. The model applied the fuzzy inference system on criteria that were difficult to define or measure due to their inherent vagueness and complexity. A separate model was applied for other well defined criteria using AHP. For the fuzzy logic model, each criterion was evaluated by the "pressure-state-response" model. Pressure, state and responses became sub-criteria of each criterion and they were characterised by fuzzy sets. The rules were exemplified as "*IF pressure is F_{11} AND state is F_{12} AND response F_{13}*". The Mamdani's inference process was applied to aggregate all the truncated inferred fuzzy sets. The aggregated fuzzy sets were defuzzified using the centre of gravity method to give a crisp output utility for each country. The utilities were used to rank the environmental sustainability of different countries.

Raj and Kumar (1998) offered another approach to rank river basin planning alternatives using only fuzzy numbers. The alternatives are evaluated directly by the experts using fuzzy numbers with respect to each criterion. Each criterion is also given a weight using fuzzy numbers by the experts. The total utility of each alternative is determined by performing fuzzy arithmetic on the weighted fuzzy numbers.

D2 Fuzzy measure: Choquet integral

The Choquet integral, $C_\mu(x)$, with respect to a discrete fuzzy measure μ is given by Eqn D-8:

$$C_\mu(x) = x_{\tau(i)}\mu(N) + \sum_{i=1}^{n}\left(x_{\tau(i)} - x_{\tau(i-1)}\right)\mu(\{\tau(i), \dots, \tau(n)\}) \qquad \textbf{D-8}$$

where τ is a non-decreasing permutation of the input x $(x_{\tau(1)} \leq x_{\tau(2)} \leq \cdots \leq x_{\tau(n)})$.

D2.1 k-additive measure

The Choquet integral is able to represent interaction criteria, ranging from redundancy (satisfaction of neither criteria contribute to a significant effect on aggregated performance), to positive synergy (satisfaction of either criterion contribute to a significant effect on aggregated performance) (Grabisch, 1996). However, 2^n coefficients are required to be defined for the Choquet integral according to Eqn D-8. To reduce the number of coefficients, a special family of fuzzy measure called the k-additive measure was developed by Grabisch (1997).

k is the number of criteria in which interaction is defined for, $|A| = k$ but whenever the coalition A has more than k criteria, $|A| > k$, there is no interaction. By imposing the k-additive measure, the complexity is reduced from 2^n to $1 + \sum_{i=1}^{k} \binom{n}{i}$. A 1-additive measure is simply an additive measure which requires *n* coefficients. The 2-additive measure considers interaction between a pair of criteria, which requires only $\frac{n(n+1)}{2} - 1$ coefficients. This is a practical and useful case because interaction between more than two criteria is difficult to comprehend. CI with 2-additive measure can be defined based on two parameters instead of μ: Shapley values (ϕ_i) and the Interaction indices (*Iij*) (see below).

D2.2 Shapely value

The Shapley value originates from game theory. A central concept in game theory is value. Suppose N is a set of players, the subset A⊂N is a coalition and μ is the worth of the game or the amount the players will earn in the game *μ(X)*. The problem is to find out the monetary value of a single player if the total value of the game is known. The Shapley value represents the true contribution of a player and satisfies the condition $\sum_{i=1}^{n} \phi_i = 1$. Extending the analogy from game theory to CI, the Shapley value can represent the weight of each elementary criterion in relation to the criterion's contribution to the overall value, defined as:

$$\phi_i = \sum_{K \subset N \setminus i} \frac{(n-k-1)!\,k!}{n!} [\mu(K \cup \{i\}) - \mu(K)] \qquad \textbf{D-9}$$

with $k := |K|$. If the fuzzy measure is additive (1-additive measure), then $\phi_i = \mu(\{i\})$.

D2.3 Interaction index

Interaction between criteria can either be positive (complimentary) or negative (disjunctive). The basic form for interaction between a pair of criteria i, j can be described as $\mu(i,j) - \mu((i) - \mu(j)$. However, this additive property is not sufficient to model the interaction between criteria. The Interaction index $I_{ij} \in [-1,1]$, proposed by Murofushi and Soneda (1993), measures the level of interaction between pairs of criteria, and is defined as:

$$I_{ij} = \sum_{K \subset X \setminus ij} \frac{(n-k-2)!\,k!}{(n-1)!} [\mu(K \cup \{i,j\}) - \mu(K \cup \{i\}) - \mu(K \cup \{j\}) + \mu(K)] \qquad \textbf{D-10}$$

- A positive I_{ij} indicates that the synergetic effect of the criteria I and j is significant for the aggregated performance but the satisfaction of either one of the criterion has no effect.
- A negative I_{ij} indicates the satisfaction of either criterion contributes to a significant effect on the aggregation performance.
- A I_{ij} close to zero indicates that neither of the criteria contribute to a significant effect on the aggregated performance.

The aggregation for the 2-additive CI based on ϕ_i and I_{ij} is defined as:

$$q = \sum_{i=1}^{n} \phi_i x_i - \frac{1}{2} \sum_{i=1}^{n} I_{ij} |x_i - x_j| \qquad \textbf{D-11}$$

D3 Aggregation functions

This section presents the basic concepts of aggregation functions and provides justification for the selected aggregation function family. In this section three main families of aggregation functions are introduced.

There are three main families of aggregation functions (Beliakov *et al.*, 2007):

1. Conjunction aggregation representing the logical "AND" and disjunctive aggregation representing the logical "OR"
2. Mixed aggregation
3. Averaging aggregation.

These three aggregation families are briefly explained in the following section. The mathematical properties of each aggregation function can be found in Beliakov *et al.* (2007).

D3.1 Conjunction and disjunction functions

Conjunction and disjunction are suitable for situations where the aggregations are represented by the logical (AND) and the logical (OR) respectively. An aggregation function that has conjunctive behaviour is bounded by $f(x) \leq min(x_1, x_2, \ldots, x_n)$. Conjunction is non-compensatory; meaning that low scores for some criteria cannot be compensated by high scores for other criteria. For example, to pass a driving test one has to perform satisfactorily in all components during the practical driving test. Failure to meet any one of the components (e.g. blind spot checking) can result in an overall failure for the driving test despite performing satisfactorily in all other components.

An aggregation that has disjunctive behaviour is bounded by $f(x) \geq max(x_1, x_2, \dots, x_n)$, and hence the maximum score pushes the total score up. Consider the case for having influenza. Having a running nose is a symptom of flu, and so is having a fever or having a headache. Anyone of these symptoms indicates the sign of flu, and the combination reinforces the strength of it.

Two popular families under the conjunction and disjunction aggregation are triangular norm (t-norm) and triangular conorm (t-conorm). T-norm is a bivariate conjunction aggregation function which involves two arguments to produce an unique output ($T: [0,1]^2 \rightarrow [0,1]$). T-conorm is a bivariate disjunction aggregation function which involves two arguments to produce an unique output ($S: [0,1]^2 \rightarrow [0,1]$). Some typical examples of t-norm and t-conorm are:

T-norm	T-conorm
$T(x, y) = \min(x, y)$	$S(x, y) = \max(x, y)$
$T(x, y) = \max(0, x + y - 1)$	$S(x, y) = \min(1, x + y)$

D3.2 Mixed functions

The mixed aggregation function is suitable for situations where the input arguments are bipolar (i.e. inputs are measured by positive and negative values). Mixed aggregation function exhibits different aggregation behaviour such as conjunctive, disjunctive and average behaviour depending on the input argument values. For example, this aggregation function becomes disjunctive when input scores are high for reinforcing each other. It becomes conjunctive when the input scores are low for pulling each other down. If some values are high and some values are low, then this aggregation function becomes averaging. Two popular families under this class are uninorm and nullnorm.

Uninorm is a bivariate aggregation function (involves two arguments) $F: [0,1]^2 \rightarrow [0,1]$ which exhibits conjunctive behaviour when dealing with lower input argument values, disjunctive behaviour for high input argument values, and averaging otherwise. Similarly, nullnorm exhibits disjunctive behaviour for high input values, conjunctive for low input values, and averaging otherwise.

D3.3 Averaging functions

Averaging is the most common way of aggregating inputs. It is an aggregation function bounded by the maximum and minimum input argument *x*, $\min(x) \leq F(x) \leq \max(x)$. Minimum and maximum functions are considered as the limiting case for averaging. There are four groups of averaging functions. They are the classical average, median, ordered weighted average (OWA) and the fuzzy integral (Choquet and Sugeno integrals). Orness is an important concept in average aggregation. It measures the difference a given aggregation function is from the maximum function. For an aggregation function *f*, the orness measure is defined as:

$$orness(f) = \int_{[0,1]^n} \frac{f(x) - \min(x)}{\max(x) - \min(x)} dx$$

D3.4 Comparisons of the three aggregation function families

The applicability of the three aggregation function families in this research are evaluated here to show the preferred function. The first aggregation function family introduced, conjunction and disjunction are useful in either the logical “AND”, “OR” situations where either the maximum or minimum case would suffice. The global values (aggregated outputs) obtained can be skewed by the extreme inputs due to the minimum and maximum functions. Conjunction is useful in non-compensatory situations and can be skewed by a very low score. This can be explained by an example where an astronaut who failed to meet a specific qualification would fail to be selected despite how well he/she satisfied other requirements. Disjunction is useful for mutual reinforcement of the input arguments but a particular strong input can push the aggregated score up. This is similar to the example where one or two high property prices can push the average real estate price up. However, in most cases, compensation between high and low criteria performances is closer to the true spirit of trade-offs than maximum or minimum functions. Conjunctive and disjunctive are therefore not suitable aggregation functions for this research since making trade-offs are central to the preference modelling in this case.

The second aggregation function family, mixed aggregation, on the other hand is suitable when the input arguments are measured by a bipolar scale to take advantage of its changing features. If the input argument values are negative, the mixed aggregation function will display conjunctive behaviour (i.e. *v(x)=min(x)*). Contrastingly, if the input argument values are positive, the mixed aggregation function will display disjunctive behaviour (i.e. $v(x)=max(x)$). In this research, the input arguments represented by the criteria scores are measured by a unipolar scale (i.e. 0 – 100). It is not necessarily to consider changing features between conjunction and disjunctive behaviour. In view of the advantages and disadvantages of the three aggregation function families, averaging is more appropriate. The averaging function allows compensation to be made in between high and low input argument values and it does not fluctuate in between conjunctive and disjunctive behaviours.

Appendix E. Questionnaires and Supplementary Information for Interview

E1 Research Information & Consent

THE UNIVERSITY OF NEW SOUTH WALES

WRC
WATER RESEARCH CENTRE

Approval No: 08/2008/16

THE UNIVERSITY OF NEW SOUTH WALES

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Development of an integrated sustainability framework for best practice management of urban water systems

You are invited to participate in a study of "*Development of an integrated sustainability framework for best practice management of urban water systems*". We hope to learn how to better support decision making in urban water management using Multi-Criteria Decision Analysis. You are selected as a possible participant in this study because your role as a water resource planner/water expert/water user can provide invaluable insights.

If you decide to participate, we will conduct an interview. In the interview, we will obtain your preferences over a decision making problem concerning the sustainability of alternative water supplies. The interview will take approximately an hour.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by the law. If you give us your permission by signing this document, your input will form part of Elizabeth Lai's thesis and a journal article. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed about the outcome.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Elizabeth Lai (02 9385 5776, e.lai@student.unsw.edu.au) will be happy to answer them.

You will be given a copy of this form to keep.

THE UNIVERSITY OF NEW SOUTH WALES

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Development of an integrated sustainability framework for best management practice of urban water systems

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

…………………………………………………………	…………………………………………………………
Signature of Research Participant	Signature of Witness
…………………………………………………………	…………………………………………………………
(Please PRINT name)	(Please PRINT name)
…………………………………………………………	…………………………………………………………
Date	Nature of Witness

REVOCATION OF CONSENT

Development of an integrated sustainability framework for best management practice of urban water systems

I hereby wish to **WITHDRAW** my consent to participate in the research proposal described above and understand that such withdrawal **WILL NOT** jeopardise any treatment or my relationship with The University of New South Wales.

…………………………………………………………	…………………………………………………………
Signature	Date

…………………………………………………………
Please PRINT Name

The section for Revocation of Consent should be forwarded to Elizabeth Lai, School of Civil and Environmental Engineering, The University of New South Wales, Kensington, NSW 2052, e.lai@student.unsw.edu.au.

E2 Main Study Questionnaire

Workbook for Gold Coast Water Future assessment

Name: ______________________

Introduction

- This workbook has been prepared for use in workshops discussing water strategy planning for Gold Coast Water for the next 50 years as a case study.
- The actual Gold Coast Water Future started the investigation in 2004, the strategy assessment was carried out in 2005 and in 2006 the preferred strategy was selected. As information and technology evolve, the selected strategy was revised in 2007.
- This research is based on the 2005 Water Supply Strategies assessment.

Aims & objectives

- The aim of the research is to develop a framework for supporting urban water management decision making.
- Participants are asked to express their preferences in relation to a range of issues related to the case study.
- The objective is to evaluate different multi-criteria decision models using the preferences collected.

Point to note

- The value judgements expressed in the workshops will all require careful thinking and some may require difficult choices.
- Please use pencil to fill in the survey to allow for change of judgement.

Background

Gold Coast Water (GCW) has traditionally relied heavily on sourcing water from dams. However, changing climate and rainfall patterns have made these sources less reliable. Continues population growth also means water demand is likely to increase from 150 ML/day (million liters per day) in 2005 to 466 ML/d (total demand) in 2056. To meet the increasing water demand, GCW had to identify a water supply strategy suitable for Gold Coast over the next 50 years. The strategy aimed to involve alternative water supplies such as desalination, recycled water, rainwater tanks to reduce reliance on dam water resources.

Proposed strategies

There are five proposed strategies and all of the strategies included the existing Hinze Dam, water conservation and pressure management. The strategies differed by the contribution from each of the four water sources (recycle water, rainwater, desalination and raising dam capacity). The four water sources are explained in Table 1 and the breakdown of the components is shown in Figure 1.

Table 1 Water sources

Water sources	Measures
Raise Hinze Dam (Dam)	The height of the dam wall by 15 metres, Increase water supply from 191 to 225 ML/d
Rainwater tanks (RWT)	RWT will provide 20 ML/d to the city by 2056, currently it is providing 0.5 ML/d Installation of rainwater tanks are mandatory in new development areas
Recycled water (RW)	Gold Coast reused 16.7% of all recycled water produced (7960 ML/d) in 2008/9 Aimed to increase the use of recycled water to around 80% by 2056
Desalination (Desal)	The desalination plant has the capacity to supply up to 133 ML/d The plant has been in operation since Feb 09

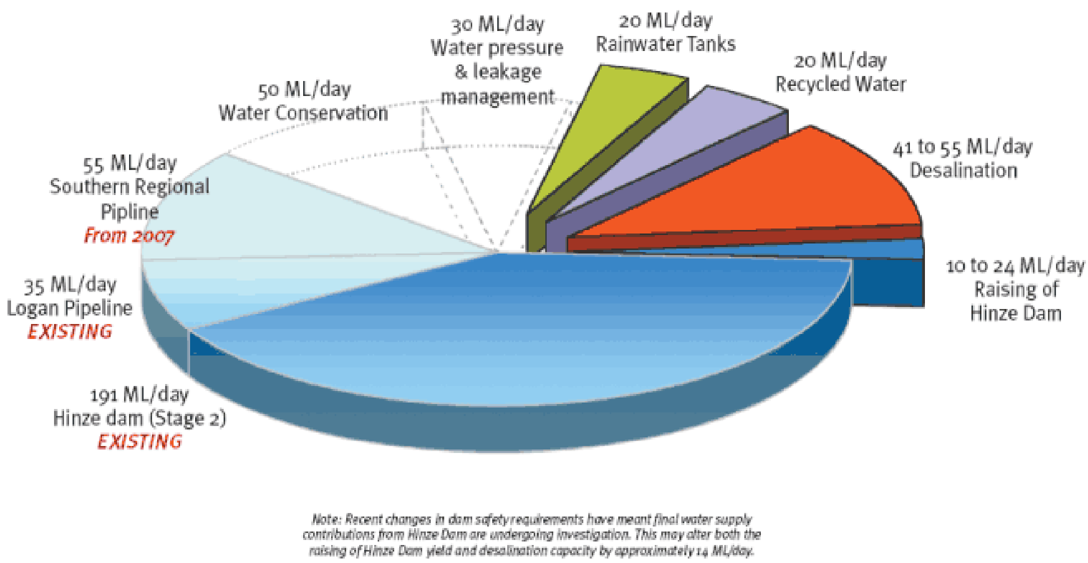


Figure 1 Gold Coast original water strategy 2005

Table 2 Water strategies from combinations of multiple water sources (based on 2005 strategy)

	Strategies	Details	Pros	Cons
A	**Raise dam capacity**	• Most conventional strategy • Incorporates raising of Hinze Dam • Moderate supply contributions from RWT, RW and Desal.	• Business as usual • Less complex infrastructure (rainwater/recycl e water)	• Reliability issues with the dam • Flexibility low • Drought restriction • Ecosystem disturbed
B	**High Desalination**	• Assumes that Hinze Dam is not raised • Desalination as the main future source • RWT and RW not major source	• Lower life cycle cost (lower O&M cost from RWT and RW) • Less likely to warrant water restriction	• High greenhouse gas emission
C	**Balance**	• Assumes that Hinze Dam is raised • Lower usage of RWT and RW • Higher long term reliance on Desal	• Balanced range of initiatives • Higher likelihood of community acceptance • High flexibility	• Moderate to High greenhouse gas emission due to relatively high reliance on desalination
D	**No dam raising**	• Essentially the same as Strategy A except Hinze Dam is not raised	• Better environmen tal performanc es •	• Low likelihood of community acceptance
E	**Recycled water and rainwater tanks**	• Assumes that Hinze Dam is raised • The use of RWT and RW will be developed to a significant level • Reduce the long-term reliance on seawater desalination.	• Better environmen tal performanc es • High exposure to risk due to complexity of infrastructure	• Highest life cycle cost • Lower likelihood of community acceptance • High impact on local community due to brownfield implementation

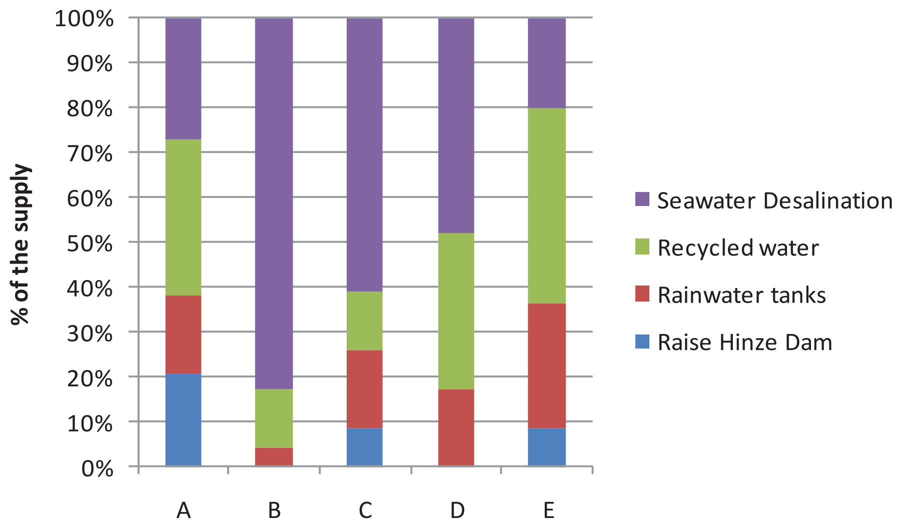


Figure 3 Comparison between the five strategies A to E (based on 2005 strategy assessment)

Table 3 Breakdown of the water sources contribution (based on 2005 strategy assessment)

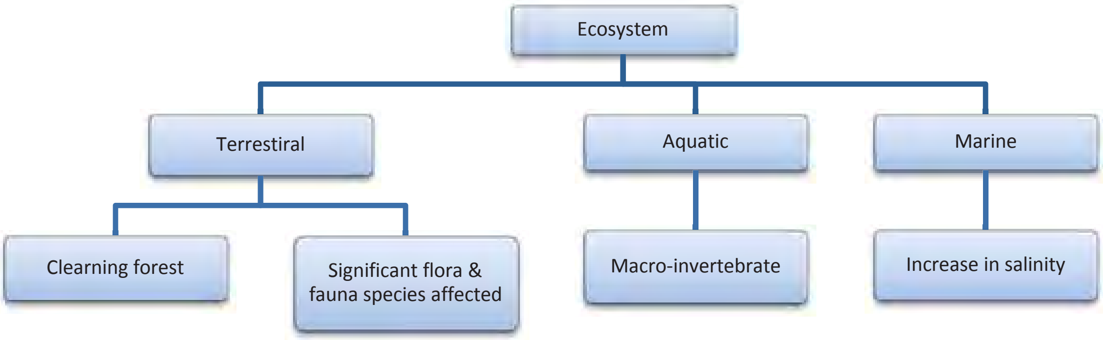
Key Water Sources (ML/d)	A Dam raising	B Desal	C Balance with more in desal	D Balance in RW & RWT & Desal No dam raising	E Balance in more RW & RWT
Raise Hinze Dam	24	0	10	0	10
Rainwater tanks	20	5	20	20	32
Recycled water	40	15	15	40	50
Seawater Desalination	31	95	70	55	23
Other key measures*	351	351	351	351	351
Total Supply Capacity	**466**	**466**	**466**	**466**	**466**

Table 4 Percentage contribution in the water balance (based on 2005 strategy)

	A Dam raising	B Desal	C Balance with more in desal	D Balance in RW & RWT & Desal No dam raising	E Balance in more RW & RWT
Raise Hinze Dam	5%	0%	2%	0%	2%
Rainwater tanks	4%	1%	4%	4%	7%
Recycled water	9%	3%	3%	9%	11%
Seawater Desalination	7%	20%	15%	12%	5%
Other key measures*	75%	75%	75%	75%	75%
Total	100%	100%	100%	100%	100%

*Other key measures include: Hinze Dam stage 2, Logan pipelines, Southern regional pipeline, water conservation, water pressure and leakage management.

1 Environmental Impacts – Ecosystem



Ecosystem	Criteria	Impact
Terrestrial	1. Forest (Fo)	a) Hectares of remnant vegetation (vegetation that support habitat for fauna and flora species) being cleared
	2. Flora and Fauna (FF)	b) Significant flora species and significant fauna species affected by the clearance of vegetation
Aquatic	3. Macroinvertebrate (Ma)	c) The loss of macroinvertebrate[29] community (i.e. snails, slugs, dragonfly) that support the health of waterways
Marine	4. Salinity (Sa)	d) Increase in salinity level due to brine discharge, affecting a range of marine organisms

	Hinze Dam	Rainwater	Recycle Water	Desalination
Clearing Forest	24 ML/d - 440 ha 10 ML/d 50 ha	Nil	6 ha Staplyton WWTP	Nil
Significant flora and fauna species	19 flora species 17 fauna species	Nil	7 flora species 17 fauna species	8 flora species
Macro-invertebrate	Nerang River below dam significantly impaired[30]	Nil	Pimpama Coomera WWTP release into Pimpama River and Broadwater Impact similar to reference level[31]	Nil
Marine salinity due to brine discharge	Nil	Nil	Nil	Brine discharge maximum increasing to 37.5 ppt (normal 35.5 ppt)

Task 1 Please rank the ecosystem criteria (Fo, FF, Ma, Sa) from 1 (least important) to 4 (most important) and then rate the strength of the preference using the following scale.

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred
0	1	2	3	4	5	6

---

[29] Macroinvertebrates are animals without backbones, large enough to be seen with the naked eye, (e.g. snails, mussels, shrimps, crayfish, dragonflies, mayflies and midges). Macroinvertebrate are very useful indicators for the health of waterways.

[30] Fewer families than expected. Potential impact either on water and/or habitat quality resulting in a loss of families. Between 20% and 50% of the expected macro-invertebrate families have been lost.

[31] Expected number of families within the range found at 80% of the reference sites.

Task 2 If you are given a sum of money $100 million to avoid the following stated impacts, how much would you spend on each item of impact?

	Rank 4 Most important	>	Rank 3	>	Rank 2	>	Rank 1 Least important
Preference							
Mitigation value $100m		-		-		-	

Ecosystem Criteria	Worst (0)	Best (100)
Hectare of vegetation cleared (Fo)	450 hectares	0 hectares
Significant flora and fauna species affected (FF)	80 species	0 species
Loss of Macroinvertebrate community (Ma)	75%	0%
Number of marine organisms affect by increased salinity level (Sa)	5	0

Task 3 Please rank the following options from 1 (least preferred) to 6 (most preferred)

Criteria at their best	**1 Forest + FF**	**2 Forest + Macro-I**	**3 Forest + Salinity**	**4 FF + Macro-I**	**5 FF + Salinity**	**6 Macro-I + Salinity**
Vegetation cleared	0 ha	0 ha	0 ha	450 ha	450 ha	450 ha
Flora and fauna species	0 species	80 species	80 species	0 species	0 species	80 species
Macroinvertebrate	0%	100%	0%	100%	0%	100%
Salinity level	40 ppt	40 ppt	35.5 ppt	40 ppt	35.5 ppt	35.5 ppt
Rank						

Task 4 Please give either rankings (1 (worst) – 5 (best)) **OR** ratings from 0 to 100 according to the performance of the options (<50 fail, 50-65 pass, 65-75 credit, 75-85 distinction and >85 high distinction). The scores can be changed according to your judgement.

	Criteria	A		B		C		D		E	
1a	Vegetation cleared	1		99		88		99		88	
1b	Flora and fauna	18		79		60		63		39	
1c	Macroinvertebrate	60		90		70		80		80	
1d	Marine organisms	80		60		60		60		80	
	Ranking or rating										

2 Environmental Impact – overall

- **Task 1** Please rank the following impacts from 1 to 2, **1** being the **worst impact** you want to avoid the most and **2** the **better impact** that you least worried about.

1 worst impact ⟷ 2 better impact

- **Task 2** If you are given a sum of money \$100 million to avoid the following stated impacts, how much would you spend on each item of impact? (Note: spending the \$100 million on either one of the impacts can mitigate or eliminate the problem entirely)

Rank	Mitigation value Trade-off (\$millions)	Impact
		1. Loss of high value ecosystem – 450 ha remnant vegetation lost / 80 flora & fauna species / 75% Macroinvertebrate community (severely impaired) / 5 marine organisms affected by increase salinity
		2. 1.2% increase in annual tCO_2-eq embodied emission per capita for the Gold Coast population (302,400 tCO_2-eq in 2056 equivalent to putting additional 70,000 cars on the road year or increase 4700 household tCO_2-eq emissions per year)
Total	\$100 million	

- **Task 3** Please give either rankings (1 (worst) – 5 (best)) **OR** ratings from 0 to 100 according to the performance of the options (<50 fail, 50-65 pass, 65-75 credit, 75-85 distinction and >85 high distinction). The scores can be changed according to your judgement.

	Criteria	A	B	C	D	E
1	Loss of high value ecosystem	44	68	68	76	78
2	Greenhouse gas	67	18	37	47	74
	Ranking or rating					

3 Technical Impacts

		Impacts
3	Security of supply	a) Insecure water source – 100% reliance on only dam water (business as usual)
4	Reliability of services	b) Unreliability water sources – medium water restriction[32] likely to be required all year round due to reliance on climate sensitive water sources
5	Flexibility	c) Low flexibility – inability to adapt to new strategy (i.e. indirect potable reuse of recycle water) due to lack of infrastructure
6	Risk	d) High risk profile – complex infrastructure (recycle water system risk of cross contamination)

- **Task 1** Please rank the technical criteria from 1 (the least important) to 4 (the most important) and then rate the strength of the preference using the following scale.

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred
0	1	2	3	4	5	6

- **Task 2** If you are given a sum of money $100 million to avoid the following stated impacts, how much would you spend on each item of impact? (Note: spending the $100 million on either one of the impacts can mitigate or eliminate the problem entirely)

	Rank 4 Most important	>	Rank 3	>	Rank 2	>	Rank 1 Least important
Preference							
Mitigation value $100m		-		-		-	

[32] Existing gardens and lawns cannot be watered between 10 am and 4 pm. Outside these hours, gardens and lawns can be watered using a bucket, watering can, hand held trigger nozzle hose.

	Criteria	Worst	Best
6	Security of supply	Reliance on 1 single source	Reliance on multiple sources (i.e. dam/RW/RWT/desal)
7	Reliability of services	High reliance on climate sensitive water source	Low reliance on climate sensitive water sources
8	Flexibility	Poor operational flexibility (i.e. no diversity in provide alternative resources)	Fully capable of adapting to new changes (i.e. indirect potable water reuse)
9	Risk	Risk of cross contamination due to complex infrastructure of recycle water system	No risk of cross contamination because of no complex infrastructure associated with recycle water system

Task 2 Please rank the following options from 1 (the least preferred) to 6 (the most preferred).

Criteria at their best	**1 Security + reliability**	**2 Security + flexibility**	**3 Security + risk**	**4 Reliability + flexibility**	**5 Reliability + risk**	**6 Flexibility + risk**
Security of supply	100	100	100	0	0	0
Reliability of services	100	0	0	100	100	0
Flexibility	0	100	0	100	0	100
Risk	0	0	100	0	100	100
Rank						

Task 3 Please give either rankings (1 (worst) – 5 (best)) **OR** ratings from 0 to 100 according to the performance of the options (<50 fail, 50-65 pass, 65-75 credit, 75-85 distinction and >85 high distinction). The scores can be changed according to your judgement.

	Criteria	A	B	C	D	E
6	Security of supply	38	34	34	50	56
7	Reliability of services	58	76	64	62	72
8	Flexibility	63	53	63	60	67
9	Risk	56	69	70	63	52
	Ranking or rating					

4 Value functions

Ecosystem impacts

	Mitigation level	Worst ←--→Best				
	Choice	**$0m**	**$25m**	**$50m**	**$75m**	**$100m**
1a	Vegetation cleared	480 ha Sydney Olympic park land	360 ha equivalent to 2 Sydney Royal Botanical Garden	240 ha equivalent to Sydney Centennial Park	120 ha equivalent to Moore Park golf course	0 ha
	Choice	$0m	$25m	$50m	$75m	$100m
1b	Flora and fauna	80 significant flora & fauna species affected	60 significant flora & fauna species affected	40 significant flora & fauna species affected	20 significant flora & fauna species affected	0 significant flora & fauna species affected
	Choice	$0m	$25m	$50m	$75m	$100m
1c	Macroinvertebrate community (% of biodiversity left)	Biodiversity extremely impaired 20%~40% biodiversity left	Biodiversity severely impaired 40%-60% biodiversity left	Biodiversity significantly impaired 60%~80% biodiversity left	Biodiversity close to reference site 80%~100% biodiversity left	Biodiversity more than reference site 100%
	Choice	$0m	$25m	$50m	$75m	$100m
1d	Marine organisms affected due to brine discharge	4 marine organisms affected	3 marine organisms affected	2 marine organisms affected	1 marine organism affected	0 marina organism affected

Environmental impacts

	Mitigation level	Worst ←--→Best				
	Choice	$0m	$25m	$50m	$75m	$100m
1	Loss of high value ecosystem	480 ha forest cleared / 80 flora & fauna species affected / 20-50% biodiversity left in waterways / 4 marine organisms affected	360 ha forest cleared / 60 flora & fauna species affected / 40-60% biodiversity left in waterways / 3 marine organisms affected	240 ha forest cleared / 40 flora & fauna species affected / 60-80% biodiversity left in waterways / 2 marine organisms affected	120 ha forest cleared / 20 flora & fauna species affected / 80-100% biodiversity left in waterways / 1 marine organisms affected	0 ha forest cleared / 0 flora & fauna species affected / 100% biodiversity left in waterways / 0 marine organisms affected
	Choice	$0m	$25m	$50m	$75m	$100m
2	Greenhouse gas	1.2% increase in per capita tCO_2-eq (extra 70,000 cars on road)	1.02% increase in per capita tCO_2-eq (extra 60,000 cars on road)	0.85% increase in per capita tCO_2-e (extra 50,000 cars on road)	0.67% increase in per capita tCO_2-eq (extra 40,000 cars on road)	0.49% increase in per capita tCO_2-eq (extra 30,000 cars on road)

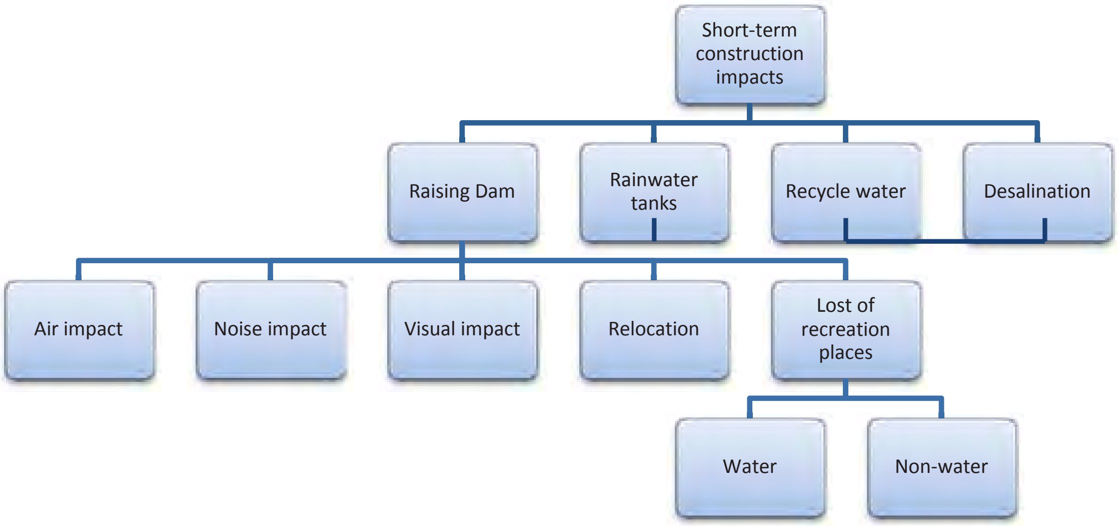
Technical and overall impacts

	Mitigation level	Worst ←--→Best				
	Choice	$0m	$25m	$50m	$75m	$100m
3	Security of supply	Only relay on 1 source (dam)	Equal reliance on 2 sources (dam + RW)	Equal reliance on 3 sources (dam + RW + RWT)	Rely on 4 sources (dam + RW + RWT + desal) but higher emphasis on desal	Equal reliance on dam/RW/RWT/desal
	Choice	$0m	$25m	$50m	$75m	$100m
4	Reliability of services	80%-100% of water demand is dependent on climate sensitive resources	60%-80% of water demand is dependent on climate sensitive resources	40%-20% of water demand is dependent on climate sensitive resources	20%-0% of water demand is dependent on climate sensitive resources	No dependence on climate sensitive water resources
	Choice	$0m	$25m	$50m	$75m	$100m
5	Flexibility (ability to incorporate indirect potable reuse once the community attitude has changed to accept it)	Very low flexibility able to incorporate indirect potable reuse with > 10 yr delay	Low flexibility able to incorporate indirect potable reuse with 5-10 yr delay	Moderate flexibility able to incorporate indirect potable reuse with 2-5 yr delay	High flexibility able to incorporate indirect potable reuse with 1-2 yr delay	Very high flexibility able to incorporate indirect potable reuse with no delay
	Choice	$0m	$25m	$50m	$75m	$100m
6	Risk (risk of cross contamination due to recycle water system)	Very high risk (less than 1 in 1000 person will be affected)	High risk (less than 1 in 5,000 person will be affected)	Moderate risk (less than 1 in 10,000 person will be affected)	Low risk (less than 1 in 50,000 person will be affected)	Very low risk (less than 1 in 100,000 person will be affected)
	Choice	$0m	$25m	$50m	$75m	$100m
7	Whole of life cost	Whole of life cost $6.5b to meet the 466 ML/d demand	Whole of life cost $6.2b to meet the 466 ML/d demand	Whole of life cost $5.9b to meet the 466 ML/d demand	Whole of life cost $5.6b to meet the 466 ML/d demand	Whole of life cost $5.3b to meet the 466 ML/d demand

E3 Pilot Study Questionnaire

1 Social Impacts

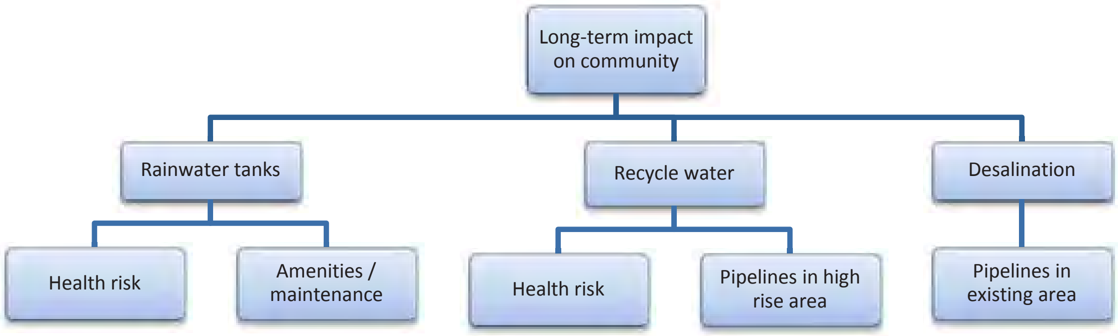
1.1 Short-term construction impacts



	Raising Hinze Dam	Rainwater	Recycle Water	Desalination
General info	9 ET sensitive receivers 60 ET residence within 1 km dam wall Construction duration 3 yrs (late 2007-10)	21,000ET to 75,000ET (greenfield) 0 to 57,000ET (brownfield)	Stapylton 7ML/d (new plant located in industrial area) Elanora 19ML/d (existing) Coombabah 9ML/d (upgrading)	Site 53 ha, plant 6.5 ha 10ET sensitive receivers Construction Sept06-Jul08 Previously a landfill
Air	1%[33] increase in risk of mortality due to exposure to average particulate matter at PM10 20 µg/m3[34]	Nil	>1% increase in risk of mortality due to exposure to average particulate matter at PM10 20 µg/m3	>1% increase in risk of mortality due to exposure to average particulate matter at PM10 20 µg/m3
Noise impact	12%[35] of high annoyance response due to noise level at Ldn = 59 dB(A)[36]	Nil	12% of high annoyance response due to noise level at Ldn = 60 dB(A)	33% of high annoyance response due to noise level at Ldn = 72 dB(A)
Relocation	2 facilities (Koala plantation world)	Nil	Nil	2 ET Soccer and Ruby fields
Recreational (non-water + water)	No access to picnic/ walking tracks/ mountain bike track/ horse riding / swimming/ boating	Nil	Nil	No access to soccer/ ruby fields/ dog off leash area/ car park / driving range / skate

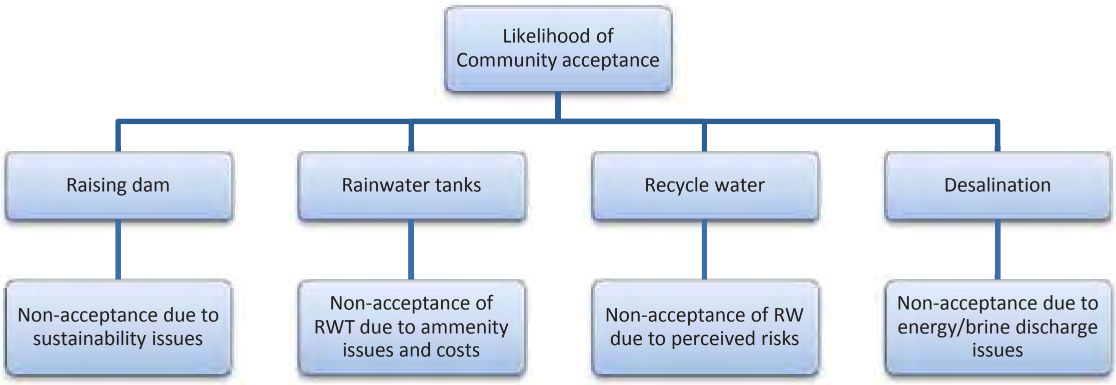
[33] % increase in daily mortality due to cardiorespiratory causes.
[34] Ambient particulate matter is 10-25µg/m3, the dust storm on the 24Sept 09 is 15,500 µg/m3. 50µg/m3 is the guideline value for construction.
[35] % Highly annoyed is the percentage of annoyance responses due to noise disturbance which exceed a certain cutoff point.
[36] Noise: day night sound level (dBA) – 35 dBA for wilderness ambient, 59 dBA urban residential area, 89 apartment next to freeway

1.2 Long term impact on community



	Hinze Dam	Rainwater	Recycle Water	Desalination
Health risks	Recreational water health risk	US EPA standard 1 in 10,000 annual risk of infection from microbial pathogens	US EPA standard 1 in 10,000 annual risk of infection from microbial pathogens	Nil
Pipelines	Nil	Nil	Brownfield in Beachside (Elanora) and Southport (Coombabah) highrise areas	24 km north to Worongary

1.3 Likelihood of community acceptance



Hinze Dam	Rainwater	Recycle Water	Desalination
Generally support because of the concept of Gold Coast being "independent"	Generally support The cost of installing rainwater tanks in existing homes may prevent many people from retrofitting them	Mix support for RW depending on degree of close personal contact uses	Desalination is widely accepted but there are concerns about its environmental impact

1.4 Assessment of social impacts

- (Ranking) Please rank the following impacts from 1 to 3, with **1 being the worst impacts you want to avoid the most** and **3 the better impact that you least worried about**.

1 worst impact ⟷ 3 better impact

- (Value trade-off) If you are given a total of $100 million to invest for mitigating the following stated impacts, how much would you spend on each item of impact?

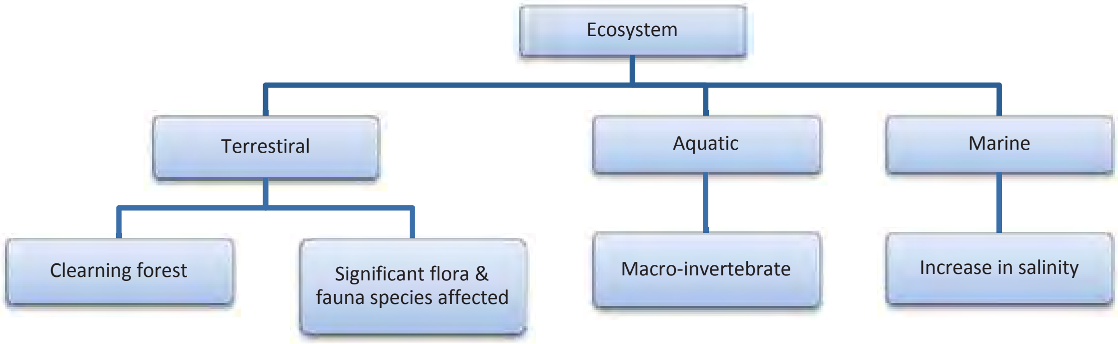
Rank	Value Trade-off ($100 millions)	Impact
		a) Short-term construction impact
		b) Long-term impacts on local community
		c) Likelihood of community acceptance
Total	$100 million	

- Please give a rating from 0 to 100 according to the performance of the options.

0 worst ⟷ 100 best

	Criteria	A Dam rising	B Desal	C Balance in all 4	D Balance in RW & RWT & Desal No dam raising	E RW & RWT
1	Short term construction impact	62	64	70	74	68
2	Long-term impacts on local community	74	68	74	68	58
3	Likelihood of community acceptance	62	62	86	66	62
	Rating					

2 Environmental Impacts – Ecosystem



Ecosystem	Criteria	Impact
Terrestrial	5. Forest (Fo)	e) Hectares of remnant vegetation (vegetation that support habitat for fauna and flora species) being cleared
	6. Flora and Fauna (FF)	f) Significant flora species and significant fauna species affected by the clearance of vegetation
Aquatic	7. Macroinvertebrate (Ma)	g) The loss of macroinvertebrate[37] community (i.e. snails, slugs, dragonfly) that support the health of waterways
Marine	8. Salinity (Sa)	h) Increase in salinity level due to brine discharge, affecting a range of marine organisms

	Hinze Dam	Rainwater	Recycle Water	Desalination
Clearing Forest	• 24 ML/d - 400 ha • 10 ML/d 50 ha	• Nil	• 6 ha Staplyton WWTP	• Nil
Significant flora and fauna species	• 19 flora species • 17 fauna species	• Nil	• 7 flora species • 17 fauna species	• 8 flora species
Macro-invertebrate	• Nerang River below dam significantly impaired38	• Nil	• Pimpama River and Broadwater similar to reference level39	• Nil
Marine salinity due to brine discharge	• Nil	• Nil	• Nil	• Brine discharge 200ML/d increasing to 37.5 ppt (normal 35.5 ppt)

[37] Macroinvertebrates are animals without backbones, large enough to be seen with the naked eye, (e.g. snails, mussels, shrimps, crayfish, dragonflies, mayflies and midges). Macroinvertebrate are very useful indicators for the health of waterways.
[38] Fewer families than expected. Potential impact either on water and/or habitat quality resulting in a loss of families. Between 20% and 50% of the expected macro-invertebrate families have been lost
[39] Expected number of families within the range found at 80% of the reference sites.

- Please rank the ecosystem criteria from 1 (most important) to 4 (least important) and then rate the strength of the preference using the following scale.

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred

Example (Rank 1 most important – Rank 4 least important)

Rank 1	>	Rank 2	>	Rank 3	>	Rank 4
Salinity	Moderately preferred	Macro-I	Strongly preferred	Flora fauna	Weakly preferred	Forest

- Please fill in the following table

Rank	>	Rank 2	>	Rank 3	>	Rank 4

		Worst	Best
1	Hectare of vegetation cleared (Fo)	450 hectares	0 hectares
2	Flora and fauna species (FF) (significant)	80 species	0 species
3	Macroinvertebrate community (Ma)	0%	100%
4	Salinity level (Sa)	40 ppt (g/L)	35.5 ppt (g/L)

- Please rank the following options from 1 (most preferred) to 6 (least preferred)

Criteria at their best	**Forest + FF**	**Forest + Macro-I**	**Forest + Salinity**	**FF + Macro-I**	**FF + Salinity**	**Macro-I + Salinity**
Vegetation cleared	0 ha	0 ha	0 ha	450 ha	450 ha	450 ha
Flora and fauna species	0	80	80	0	0	80
Macroinvertebrate	0%	100%	0%	100%	0%	100%
Salinity level (ppt)	40	40	35.5	40	35.5	35.5
Rank						

- Please give a rating from 0 to 100 according to the performance of the options.

				Scores					Normalised scores				
	Criteria	Worst	Best	A	B	C	D	E	A	B	C	D	E
7	Vegetation cleared (ha)	450	0	446	6	56	6	55	1	99	88	99	88
8	Flora and fauna (species)	80	0	66	17	32	30	49	18	79	60	63	39
9	Macroinvertebrate	0%	100%	60	80	80	60	60	60	80	80	60	60
10	Marine species (ppt)	40	35.5	36	38	37	37	36	89	44	67	67	89
	Rating												

3 Environmental Impact – overall

Please rank the following impacts from 1 to 5, 1 being the worst impacts you want to avoid the most and 5 the better impact that you least worried about.

1 worst impact ⟷ 5 better impact

If you are given a sum of money $10million to avoid the following stated impacts, how much would you spend on each item of impact?

Rank	Value Trade-off ($millions)	Impact
		1. Avoid one hectare (1 football size field) of remnant vegetation (vegetation that support habitat for fauna and flora species and riparian vegetation) being disturbed.
		2. Avoid 1% of the total fish killed in Gold Coast (1 tonne of fish) due to the discharge of treated effluent (equivalent to 12,000 person's wastewater discharge @250 L/d)
		3. Avoid 1% of the total waterways (8 hectares) polluted with algae bloom due to the installation of 5000L rainwater tanks for 200 household (equivalent to 400 ML/year stormwater saved from discharging to waterways).
		4. Avoid 1% of Gold Coast household (12,000 household) not able to able to grow low to medium salt tolerant plant permanently due to soil contamination with the use of recycled water to irrigate garden
		5. Avoid 1% increase in annual tCO_2-eq emission for the Gold Coast population (equivalent to putting 60,000 cars on the road year or increase 4000 household tCO_2-eq emissions per year)
Total	$10,000,000	

Please give a rating from 0 to 100 according to the performance of the options.

				Scores					Normalised scores				
	Criteria	Worst	Best	A	B	C	D	E	A	B	C	D	E
10	Ecosystem – Forest cleared	0	100	42	75	74	72	69	42	75	74	72	69
11	Wastewater discharge (%)	0	20	13	5	5	13	17	65	25	25	65	85
12	Stormwater discharge (%)	0	25	15	4	15	15	23	58	15	58	58	94
13	Household cannot grow plants (%)	70	10	50	19	19	50	63	33	85	85	33	13
14	Greenhouse gas(%)	1.2[3]	0.4[1]	0.66	1.06	0.91	0.82	0.61	67	18	37	47	74
	Rating												

4 Technical Impacts – multi-attribute aggregation

Please rank the following impacts from 1 to 2, with 1 being the impacts you want to avoid the most and 2 the impact you least worried about.

1 worst impact ⟷ 2 better impact

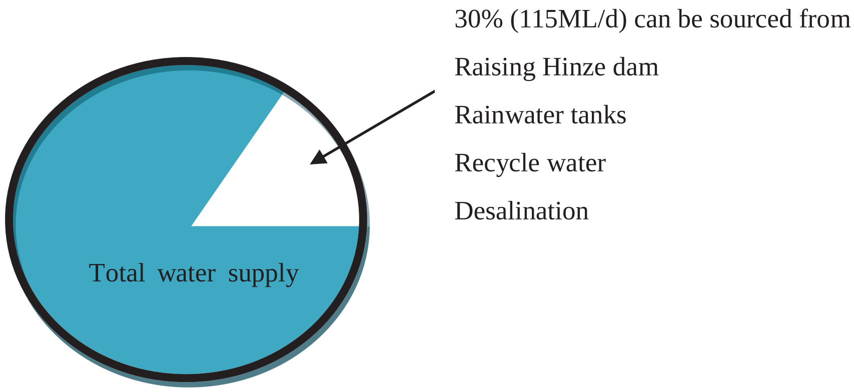
If you are given a sum of money $10million to avoid the following stated impacts, how much would you spend on each item of impact?

Rank	Value Trade-off ($millions)	Impact
		Avoid the loss of a potential 1% increase of Gold Coast city water storage (3.96ML/d = 11,314 household water need @350L/d)
		Avoid the likelihood of 1 month of medium level water restriction[1]
Total	$10,000,000	

[1]Medium water restriction means:

- Existing gardens and lawns cannot be watered between 10 am and 4 pm
- Outside these hours, gardens and lawns can be watered using a bucket, watering can, hand held trigger nozzle hose
- Guidelines: have 4 minute showers, even an efficient running shower can use 9 litres per minute
- Guidelines: turn the tap off while brushing teeth or shaving, this will save up to 8 litres per minute

Details on Impact a)



Please give a rating from 0 to 100 according to the performance of the options.

				Scores					Normalised scores				
	Criteria	Worst	Best	A	B	C	D	E	A	B	C	D	E
15	Security of supply	0%	30%	13.8	13.3	13.1	17.3	18.5	46	44	44	58	62
16	Water restriction	12 mths	6 mths	10	8.8	9.5	9.2	9.9	33	53	42	47	35
	Rating												

5 Technical Impacts – interaction aggregation

	Impact
15	Security of water supply for Gold Coast city water storage (Additional 1% storage = 3.96ML/d = 11,314 household water need @350L/d)
16	Likelihood of medium level water restriction applied

Please rank the two technical criteria for their importance and then rate the strength of the preference using the following scale.

No	Very weak	Weak	Medium	Strong	Very Strong	Extreme
0	1	2	3	4	5	6

Example

Rank 1 Most important	>	Rank 2 Least important
Water restriction	Very strong	Security of supply

Please complete the following table.

Rank 1	>	Rank 2

Imagine an option exists that is **worst** in both criteria.

How much increase in the overall attractiveness (extreme – very weak) would be if **each** criterion performance swings from worst to best (the other remains at worst)?

Compare the two swings. How much more attractive is the difference between the two swings?

		Worst	Best
17	Security of water supply	0%	30%
18	Likelihood of 1 month medium level water restriction	12 months	6 months

Please complete the following table.

	1 Security of supply	2 Likelihood of water restriction	Worst->Best
1 Security of supply	-		
2 Likelihood of water restriction	-	-	

6 Overall Value Tradeoffs

Please rank the following impacts from 1 to 4, with 1 being the worst impact you want to avoid the most and 4 the impact you least worried about.

1 worst impact ⟷ 4 better impact

Then indicate the increase in the monthly bill for a typical householder to the state impacts.

Rank	Value Trade-off Annual water bill increase	Impact
	$100	Avoid a 10% increase in the annual bill for typical residential household from $1000 to $1100 in 2009 dollars, and a corresponding increase of for all communities (council, developer and householder) which amounts to $250 m per year (on-going increase for the next 50 years).
		Avoid an inconvenience of 100 person year equivalent (on-going for the next 50 years)
		Avoid 100 hectares of remnant vegetation being cleared (out of the 2720 hectares of Springbrook national park where Hinze Dam is located.) (once off)
		Avoid the loss of 1% of Gold Coast city water storage (3.96ML/d = 11,314 household water need @350L/d)

The population in Gold Coast in 2009 is 500,000 and projected to be 1.2 million in 2056.

Please give a rating from 0 to 100 according to the performance of the options.

				Scores					Normalised scores				
	Criteria	Worst	Best	A	B	C	D	E	A	B	C	D	E
A	Economic ($b)	6.5	5.5	5.99	5.67	5.75	6.01	6.11	51	83	75	49	39
B	Social	0	100	57	65	57	65	57	57	65	57	65	57
C	Environmental	0	100	53	44	56	55	67	53	44	56	55	67
D	Technical	0	100	40	49	43	52	48	40	49	43	52	48
	Rating												

Value functions

- Please indicate a midpoint value Y such that moving from the worst level to Y is the same as moving from Y to the best level.

No.	Criteria	Impact ranges		Mid-point /Acceptable
		Worst level	Best level	
Social impacts				
1	Air quality impact	5% increase in mortality	0% increase in mortality	
2	Noise impact	40% Highly annoyed person	0%HA	
3	Visual impact	0	10	
4	Relocation	10 household	0 household	
5	Access to non-water recreational places	10 places	0 places	
6	Access to water recreational places	10 places	0 places	
7	Clearing of remnant vegetation	450 hectares	0 hectares	
8	Reduced wastewater discharge	0% (0 ML/d)	20% (50 ML/d)	
9	Reduced stormwater discharge	0% (0ML/d)	30% (30 ML/d)	
10	Household not able to grow crops vegetation due to soil contamination	65% (260,000 household)	15% (60,000 household)	
11	Greenhouse gas emission per capita annual increase	1.2% (0.25 tCO_2-eq) 70,326 cars	0.4% (0.1 tCO_2-eq) 26,000 cars	
12	Security of supply	0% (0 ML/d)	30% (115 ML/d)	
13	Likelihood of water restriction	12 months	6 months	
14	Additional increase in annual water bill	$1000	$100	

E4 Criteria Scores Explanation

	Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Social criteria					
Short-term construction impact	62	74	70	64	68
	Impacts from raising Hinze dam localized and contained Impacts are likely to arise from construction of the Recycle Water Treatment Plants (RWTP) at 3 sites Impacts may rise from construction of the recycled water pipelines in high rise area	Impacts are the least because Hinze dam is not raised Only 1 RWTP and no recycle water system in high-rise areas	Impacts are similar to A but slight better because Hinze Dame is not raised to the same extent Only 1 RWTP and no recycle water system in high-rise areas	Impacts are similar to strategy B with the following differences Impacts are likely to arise from construction of the Recycle water treatment plants at 3 sites Impacts may rise from construction of the recycled water pipelines in high rise area	Impacts should be similar to strategy C Impacts are likely to arise from construction of the Recycle water treatment plants at 3 sites Impacts may rise from construction of the recycled water pipelines in high rise area
Impacts on local community	74	68	74	68	58
	Moderate recycled water pipelines in high rise areas Pipelines from the desalination plant in excising areas Larger water surface area in Hinze Dam for recreation	Extensive pipelines from the desalination plant in existing areas	Pipelines from the desalination plant in existing areas Marginal increased water surface area	Moderate reliance on brownfield recycled water. (pipelines in high rise areas) Pipelines from the desalination plant in existing areas	High reliance on brownfield recycled water. (pipelines in high rise areas) Pipelines from the desalination plant in existing areas
Likelihood of community acceptance	62	62	86	66	62
	Moderate to high reliance on RW and RWT systems	High reliance on desalination	Range of initiatives with less reliance on single source	Moderate to high reliance on RW and RWT systems	High reliance on RW and RWT systems

	Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Ecosystem criteria					
Clearing of remnant vegetation	1	99	88	99	88
	446 ha 440 ha raising dam 6 ha from RWTP	6 ha from RWTP	56 ha 50 ha raising dam 6 ha from RWTP	6ha from RWTP	55 ha 50 ha raising dam 5 ha from RWTP
Significant flora and fauna species affected	18	79	60	63	39
	66 flora & fauna species Mostly from construction for raising dam	17 flora & fauna species Mostly from construction for RWTP and desalination	32 flora & fauna species Construction for raising dam, RWTP & desalination	30 flora & fauna species Mostly from construction for RWTP & desalination	49 flora & fauna species Mostly from construction for RWTP and desalination
Macroinvertebrate community	60	90	70	80	80
	Significantly impair the Nerang river downstream of Hinze dam which is highly disturbed already Some high value riparian zone flooded in the upper reaches of the dam 2 RWTP wastewater release (Pimpama Coomera discharges into Pimpama River and Staplyton discharges into Albert River) Impact on diversity from RWTP is minimal, macroinvertebrate close to reference site The use of RWT on 84,000ET will reduce the volume of runoff water	2 RWTP wastewater release (Pimpama Coomera discharge into Pimpama River) Impact on diversity from RWTP is minimal, macroinvertebrate close to reference site The use of RWT on 21,000ET will reduce the volume of runoff water	Significantly impair Nerang river downstream of Hinze dam which is highly disturbed already Minor high value riparian zone flooded in the upper reaches of the dam 1 RWTP wastewater release (Pimpama Coomera discharge into Pimpama River) Minimal impact on diversity from RWTP, macroinvertebrate close to ref. site Reduction in volume of runoff water by use of RWT on 84,000ET	2 RWTP release wastewater (Pimpama Coomera discharge into Pimpama River) Impact on diversity from RWTP is minimal, macroinvertebrate close to reference site The use of RWT on 84,000ET will reduce the volume of runoff water	Significantly impair the Nerang river downstream of Hinze dam which is highly disturbed already Minor high value riparian zone flooded in the upper reaches of the dam 2 RWTP wastewater release (Pimpama Coomera discharges into Pimpama River and Staplyton discharges into Albert River) Impact on diversity from RWTP is minimal, macroinvertebrate close to reference site The use of RWT on 134,000ET will reduce the volume of runoff water

	Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Marine organisms affected	80	60	60	60	80
	Brine discharge from desalination plant would be 31ML/d Salinity level likely to raise from the background 35.5 pot to 36 ppt Number of marine organisms likely to be affected = 1	Brine discharge from desalination plant would be 95ML/d Salinity level likely to raise from the background 35.5 ppt to 37.5 ppt Number of marine organisms likely to be affected = 2	Brine discharge from desalination plant would be 70ML/d Salinity level likely to raise from the background 35.5 ppt to 37.5 ppt Number of marine organism likely to be affected = 2	Brine discharge from desalination plant would be 55ML/d Salinity level likely to raise from the background 35.5 ppt to 37.5 ppt Number of marine organism likely to be affected = 2	Brine discharge from desalination plant would be 23ML/d Salinity level likely to raise from the background 35.5 ppt to 36 ppt Number of marine organism likely to be affected = 1
Environmental criteria					
Loss of high value ecosystem	44	68	68	76	78
	The clearing of vegetation associated with Hinze dam raising will be the greatest impact. RWTPs are to be located at WWTPs which are generally disturbed already	No impact form raising Hinze dam RWTPs are to be located at WWTPs which are generally disturbed already. Potential impact from the desalination brine discharge would be high (90 ML/d)	The impacts will be similar to strategy A though somewhat lower because Hinze Dam will not be raised to the same extent RWTPs are to be located at WWTPs which are generally disturbed already Potential impact from the desalination brine discharge would be high (70 ML/d)	Impacts will be similar to strategy B RWTPs are to be located at WWTPs which are generally disturbed already Potential impact from the desalination brine discharge will be lower due to decreased flows (55 ML/d)	Impacts will be similar to strategy C The potential impact from the desalination brine discharge will be low due to decreased flow

	Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Greenhouse gas emissions	67	18	37	47	74
	0.142 tCO_2e/capita net per capita greenhouse gas (GHG) emission in 2056 0.68% increase in per capita GHG Per capita emission in Australia is 21 tCO_2e	0.227 tCO_2e/capita net per capita GHG emission in 2056 1.08 % increase in per capita GHG Per capita emission in Australia is 21 tCO_2e	0.195 tCO_2e/capita net per capita GHG emission in 2056 0.93 % increase in per capita GHG Per capita emission in Australia is 21 tCO_2e	0.177 tCO_2e/capita net per capita GHG emission in 2056 0.84% increase in per capita GHG Per capita emission in Australia is 21 tCO_2e	0.131 tCO_2e/capita net per capita GHG emission in 2056 0.62% increase in per capita GHG Per capita emission in Australia is 21 tCO_2e
Technical criteria					
Security of supply	38%	34%	34%	50%	56%
	High reliance on Hinze dam Moderate reliance on RW, RWT and desalination	High reliance on desalination and lower components from RW and RWT	High reliance on desalination and lower components from RW and RWT	Slight more balance on the range of supply except with no dam raising	Less reliance on a single source More balanced reliance on the range of supply
Reliability of services	58%	76%	64%	62%	72%
	Highest reliance on climate sensitive water sources (Hinze dam, rainwater tanks)	Lowest reliance on climate sensitive water sources (rainwater tanks)	Moderate reliance on climate sensitive water sources (Hinze dam, rainwater tanks)	Moderate reliance on climate sensitive water sources (rainwater tanks)	Moderate reliance on climate sensitive water sources (Hinze dam, rainwater tanks)
Flexibility	63%	53%	63%	60%	67%
	High flexibility because of balanced reliance on the range of supply	Lowest flexibility because of high reliance on desalination and low components of RW and RWT and no raising Hinze	High flexibility because of balanced reliance on the range of supply	Moderate flexibility because of balanced reliance on RW, RWT and desalination but no raising of Hinze dam	Highest flexibility because of balanced reliance on the range of supply
Risk	56%	69%	70%	63%	52%
	High complexity of infrastructure (recycle water system)	Low complexity of infrastructure (recycle water system)	Low complexity of infrastructure (recycle water system)	High complexity of infrastructure (recycle water system)	Highest complexity of infrastructure (recycle water system)

	Strategy A	Strategy B	Strategy C	Strategy D	Strategy E
Overall					
Whole life cycle cost (Economic)	51	83	75	49	39
	$5.99 billion investment Hinze dam raising Cost due to infrastructure of RW system and O&M cost for RW and RWT Same capital cost and O&M cost for desalination plant across the strategies	$5.67 billion investment Lower capital cost for recycle water system due to less reliance on it	$5.75 billion investment Lower capital cost for recycle water system due to less reliance on it	$6.01 billion investment Cost due to infrastructure of RW system and O&M cost for RW and RWT	$6.11 billion investment Higher cost for infrastructure due to recycle water system Higher O&M cost for RW and RWT
Social	66	65	77	69	63
	See social criteria for details on the aggregated performance scores				
Environmental	56	43	53	62	76
	See environmental criteria for details on the aggregated performance scores				
Technical	54	58	58	59	62
	See technical criteria for details on the aggregated performance scores				

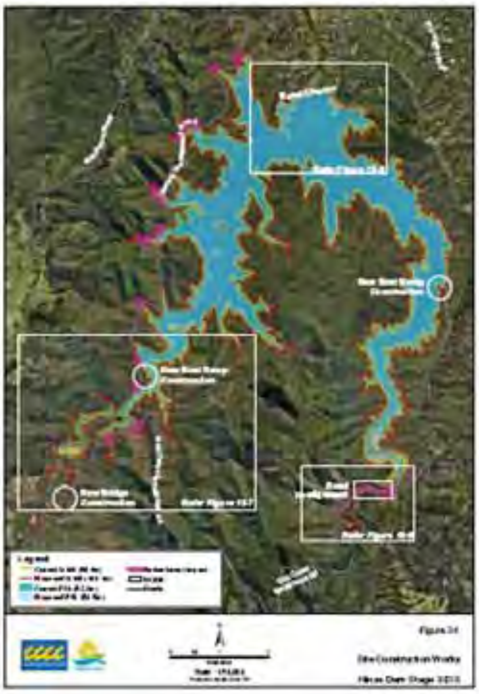
E5 Supplementary Information for Interview

Gold Coast Waterfuture

- **By 2056:**
  - Gold Coast population will more than double
    - From 500,000 to 1.2 million
  - Water needs will more than triple
    - from 185 ML/day to 396 ML/day
  - Wastewater will triple
    - 100 ML/day 300 ML/day
  - Climate and rainfall are uncertain need water security

Rising Hinze Dam

- Construction at Dam head
- Other works
  - new bridge
  - new boat ramp
  - road re-alignment



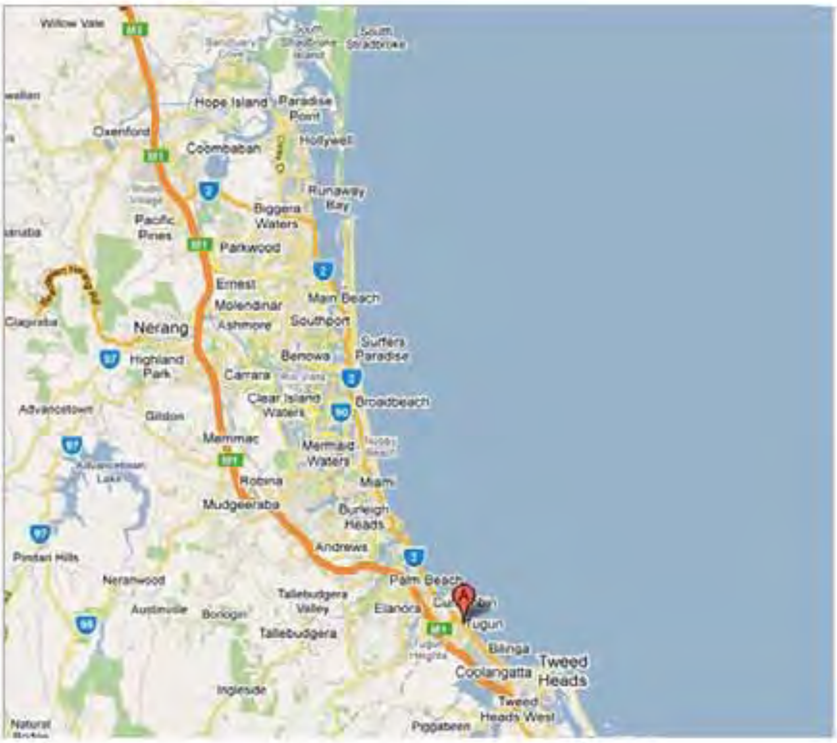
Rainwater tanks

- RWT 5 – 32 ML/d
  - 5ML/d Pimpama Coomera
  - 27 ML/d from greenfield and brownfield

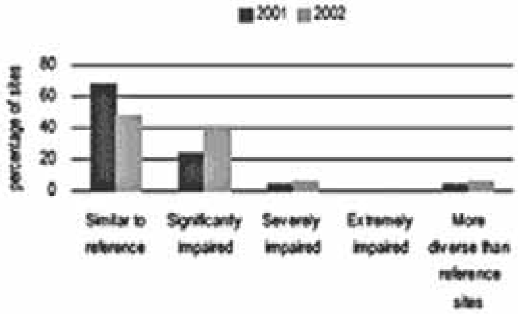
Recycle water

- RW 15 – 50 ML/d
- A. 7 ML/d Stapylton
- B. 15 ML/d Pimpama Coomera
- C. 9 ML/d Coombabah
- D. 19 ML/d Elanora


TUGUN
CORAL
SEA
Proposed Tugun Desalination Plant
GOLD COAST AIRPORT
Queensland Government
Figure 3-1
Regional Site Plan
Gold Coast Desalination Project
ERA Application


Willow Vale
Hope Island
Paradise Point
Oxenford
Coombabah
Hollywell
Runaway Bay
Biggera Waters
Pacific Pines
Parkwood
Ernest
Molendinar
Ashmore
Main Beach
Southport
Nerang
Highland Park
Benowa
Surfers Paradise
Carrara
Clear Island Waters
Broadbeach
Advancetown
Gilston
Merrimac
Mermaid Waters
Robina
Miami
Mudgeeraba
Burleigh Heads
Andrews
Pimpama Hills
Palm Beach
Neranwood
Tallebudgera Valley
Elanora
Austinville
Bonogin
Tallebudgera
Tugun
Bilinga
Tweed Heads
Coolangatta
Tweed Heads West
Ingleside
Piggabeen

Macroinvertebrate – indicator for river health



Similar to reference.	Near natural levels of biodiversity
Significantly impaired	Approximately 16–45% of biodiversity lost
Severely impaired	Approximately 46–75% of biodiversity lost
Extremely impaired	More than 75% of biodiversity lost
More diverse than reference sites	More than 15% increase in biodiversity

River condition in Queensland, 2001 - 2002

Source: Department of Natural Resources and Mines 2004, Priorities in Progress report 2003-4: A clean, liveable and healthy environment, Queensland Treasury, viewed 23 Nov 2005, http://www.treasury.qld.gov.au/office/knowledge/docs/priorities/2003-04/subsections/clean_livable_healthy.pdf

Salinity tolerances for a range of marine organisms

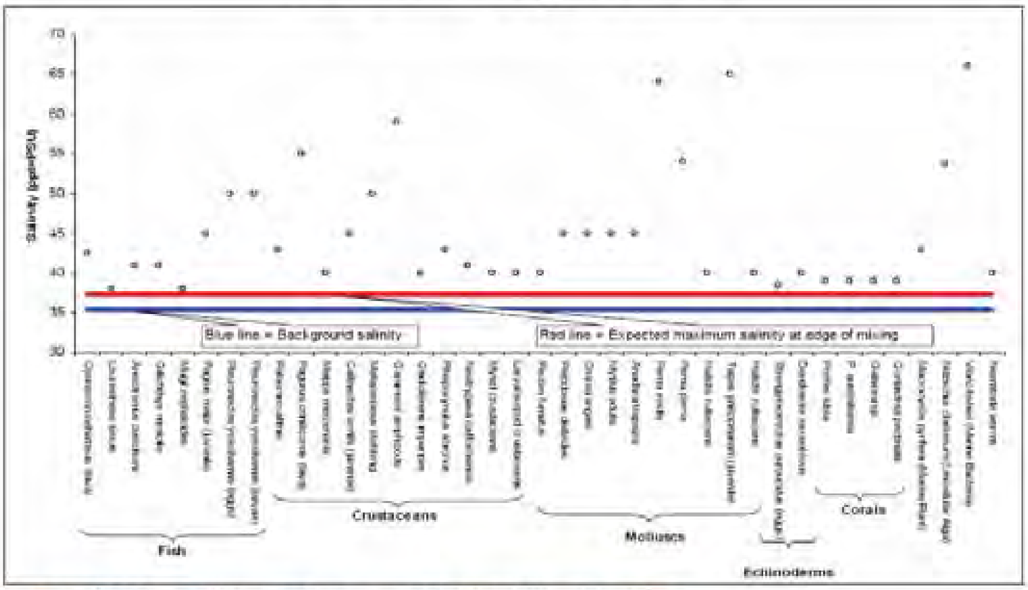
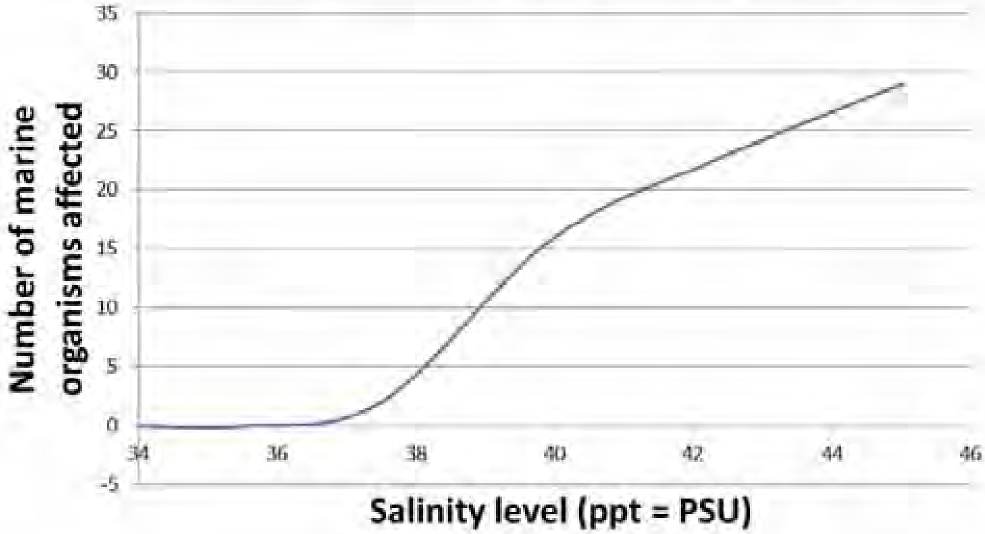
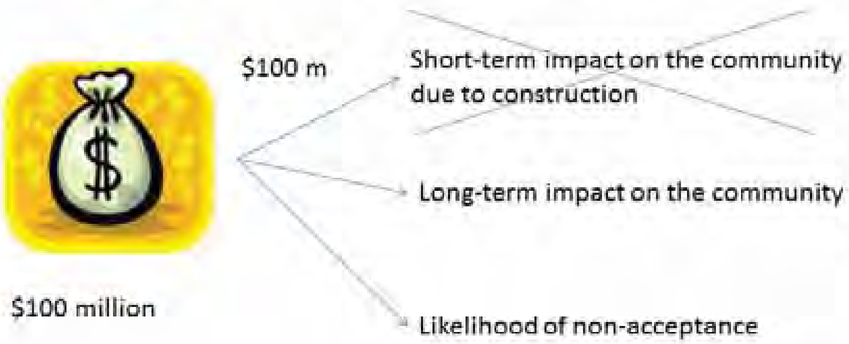


Figure 13-6 Salinity Tolerances / Sensitivities for a Range of Marine Organisms

Cumulative plot of number of organisms affected by salinity increase



Mitigation value trade-off



Mitigation scale – social impacts

	Mitigation level	0%	25%	50%	75%	100%
	Choice	1	2	3	4	5
1	Short term construction impact (duration 3 years)	Worst air/noise impact for 3 years, >10ET relocation	High air/noise impact for 3 years, > 5 ET relocation	Moderate air/noise impact (under construction guideline) for 3 years, >2 ET relocatoin	Minor air/noise impact for 3 years, no relocation	No impacts from construction at all
	Choice	1	2	3	4	5
2	Long-term impacts on local community	Aprox.1000 ET will leave next to recycling/desalination facilities and brownfield pipelines	Aprox. 750 ET will leave next to recycling/desalination facilities and brownfield pipelines	Aprox. 500 ET will leave next to recycling/desalination facilities and brownfield pipelines	Aprox. 250 ET will leave next to recycling/desalination facilities and brownfield pipelines	No disturbance on community - facilities located away from existing area and no brownfield pipelines
	Choice	1	2	3	4	5
3	Likelihood of community acceptance (A small group of community - local neigbourhood acceptanc to the 4 different water sources)	Non-acceptance of all 4 water source (dam, recycle water & rainwater tanks and desal)	Non-acceptance of 3 water source (recycle water & rainwater tanks)	Non-acceptance of 2 water source (recycle water & rainwater tanks)	Non-acceptance of 1 water source (rainwater tanks)	Acceptance of all water sources

Ecosystem assessment

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred

Rank 4 Most important	>	Rank 3	>	Rank 2	>	Rank 1 Least important
Salinity	Moderately preferred	Macroinvertebrate	Strongly preferred	Flora & fauna	Weakly preferred	Forest

Criteria at their best	**Forest + FF**	**Forest + Macro-I**	**Forest + Salinity**	**FF + Macro-I**	**FF + Salinity**	**Macro-I + Salinity**
Vegetation cleared	0 ha	0 ha	0 ha	450 ha	450 ha	450 ha
Flora and fauna	0 species	80 species	80 species	0 species	0 species	80 species
Macroinvertebrate	0%	100%	0%	100%	0%	100%
Salinity level	40 ppt	40 ppt	35.5 ppt	40 ppt	35.5 ppt	35.5 ppt
Rank						

Mitigation scale - Ecosystem

	Mitigation level	0%	25%	50%	75%	100%
	Choice	1	2	3	4	5
4	Vegetation cleared	480 ha Sydney Olympic park land	360 ha eqvialent to 2 Sydney Royal Botanical Garden	240 ha equivalent to Sydney Centennial Park	120 ha equivalent to Moore Park golf course	0 ha
	Choice	1	2	3	4	5
5	Flora and fauna	80 species	60 species	40 species	20 species	0 species
6	Macroinvertebrate community (% of biodiversity left)	Biodiversity extremely impaired 20%~40% biodiversity left	Biodiversity severly impaired 40%-60% biodiversity left	Biodiversity significantly impaired 60%~80% biodiversity left	Biodiversity close to referece site 80%~100% biodversity left	Biodiversity more than reference site 100%
	Choice	1	2	3	4	5
7	Marine organisms affected due to brine discharge	4 marine organisms affected	3 marine organisms affected	2 marine organisms affected	1 marine organism affected	0 marin organism affected

Mitigation scale - Environment

	Mitigation level	0%	25%	50%	75%	100%
	Choice	1	2	3	4	5
7	Loss of high value ecosystem	480 ha forest cleared / 80 flora & fauna species affected / 20-50% biodiveristy left in waterways / 4 marine organisms affected	360 ha forest cleared / 60 flora & fauna species affected / 40-60% biodiveristy left in waterways / 3 marine organisms affected	240 ha forest cleared / 40 flora & fauna species affected / 60-80% biodiveristy left in waterways / 2 marine organisms affected	120 ha forest cleared / 20 flora & fauna species affected / 80-100% biodiveristy left in waterways / 1 marine organisms affected	0 ha forest cleared / 0 flora & fauna species affected / 100% biodiveristy left in waterways / 0 marine organisms affected
	Choice	1	2	3	4	5
8	Greenhouse gas	1.2% increase in per capita tCO2-e (extra 30,000 cars on road)	1.02% increase in per capita tCO3-e (extra 40,000 cars on road)	0.85% increase in per capita tCO4-e (extra 50,000 cars on road)	0.67% increase in per capita tCO5-e (extra 60,000 cars on road)	0.49% increase in per capita tCO6-e (extra 70,000 cars on road)

Mitigation scale – Technical

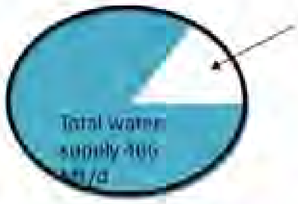
	Mitigation level	0%	25%	50%	75%	100%
	Choice	1	2	3	4	5
9	Security of supply	Only relay on 1 source (dam)	Equaly reliance on 2 sources (dam + RW)	Equal reliance on 3 sources (dam + RW + RWT)	Rely on 4 sources (dam + RW + RWT + desal) but higher emphasis on desal	Equal reliance on dam/RW/RWT/desal
	Choice	1	2	3	4	5
10	Reliability of services	80%-100% of water demand is dependent on climate sensitive resources	60%-80% of water demand is dependent on climate sensitive resources	40%-20% of water demand is dependent on climate sensitive resources	20%-0% of water demand is dependent on climate sensitive resources	No dependence on climate sensitive water resources
	Choice	1	2	3	4	5
11	Flexibility (ability to incorporate indirect potable reuse once the community attitude has changed to accept it)	Very low flexibility able to incorporate indirect potable reuse with > 10 yr delay	Low flexibility able to incorporate indirect potable reuse with 5-10 yr delay	Moderate flexibility able to incorporate indirect potable reuse with 2-5 yr delay	High flexibility able to incorporate indirect potable reuse with 1-2 yr delay	Very high flexibility able to incorporate indirect potable reuse with no delay
	Choice	1	2	3	4	5
12	Risk (risk of cross contamination due to recycle water system)	Very high risk (less than 1 in 1000 person will be affected)	High risk (less than 1 in 5,000 person will be affected)	Moderate risk (less than 1 in 10,000 person will be affected)	Low risk (less than 1 in 50,000 person will be affected)	Very low risk (less than 1 in 100,000 person will be affected)

Technical assessment

Not preferred at all	Very weakly preferred	Weakly preferred	Moderately preferred	Strongly preferred	Very Strongly preferred	Extremely preferred

Example

Rank 4 Most important	>	Rank 3	>	Rank 2	>	Rank 1 Least important
Flexibility	Moderately preferred	Risk	Strongly preferred	Security of supply	Weakly preferred	



25% (115ML/d) can be sourced from

- Raising Hinze dam
- Rainwater tanks
- Recycle water
- Desalination

Appendix F. Research Interview Data

F1 Mitigated normalising functions

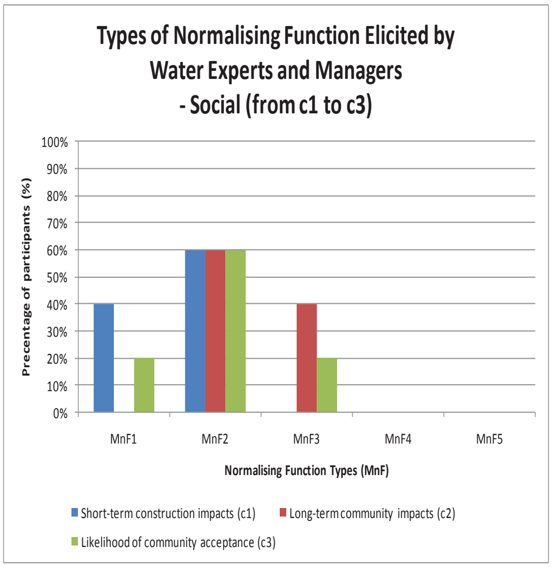
F2 Normalised criteria scores

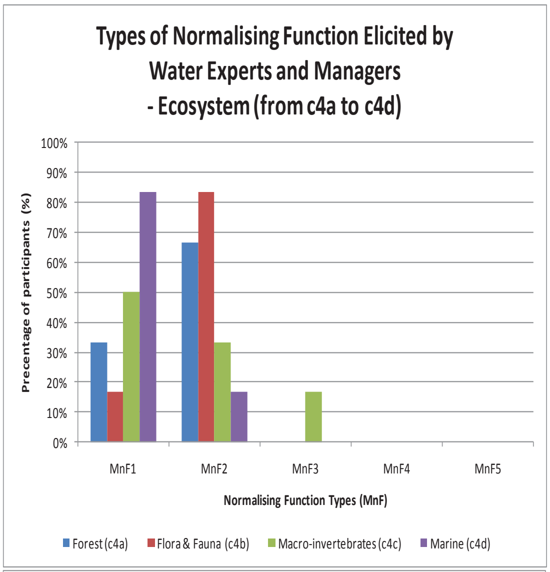
F3 Observed global values by Water Experts/Managers/Users

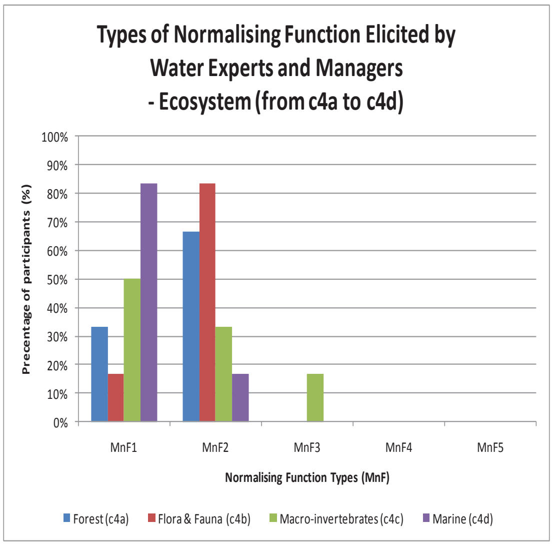
F4 Calculated global values vs. Observed global values scatter plots

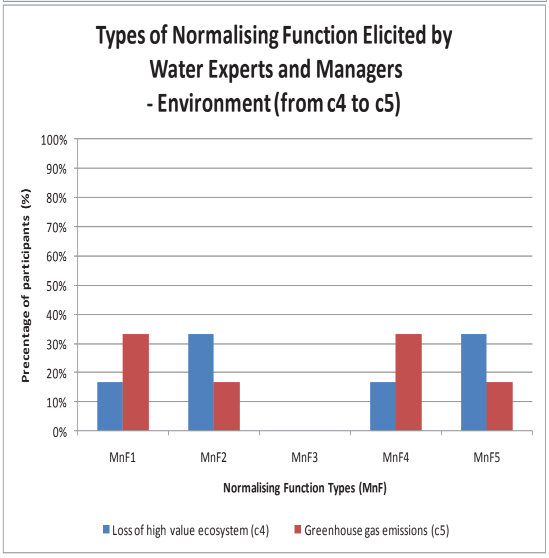
F5 Preference for Choquet Integral

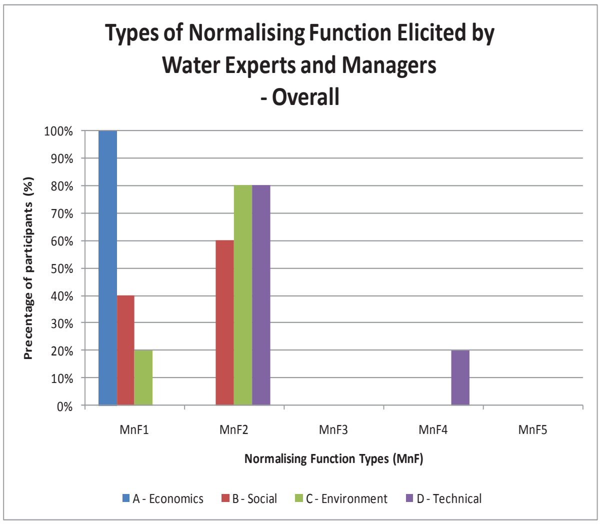
F1 Mitigated Normalising Function Types (MnF) elicited by Water Experts/Managers

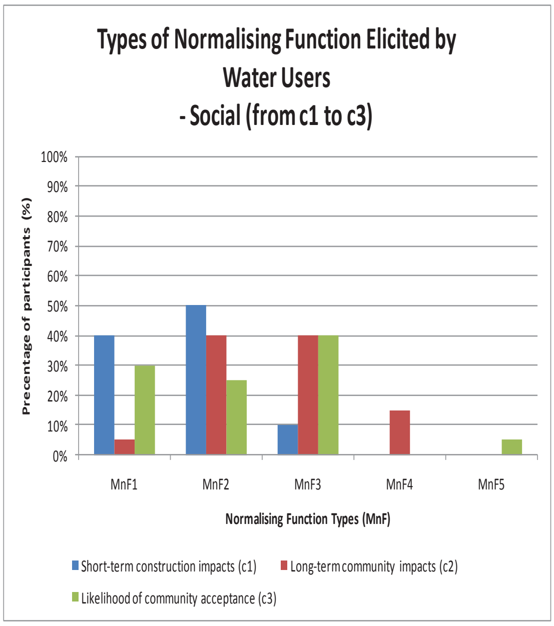


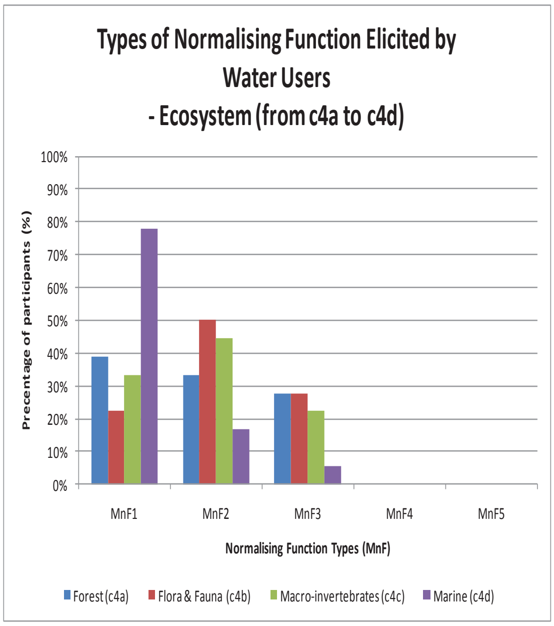


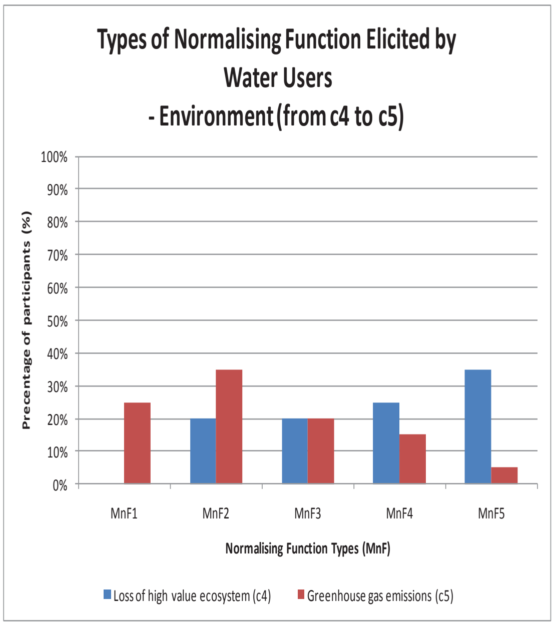


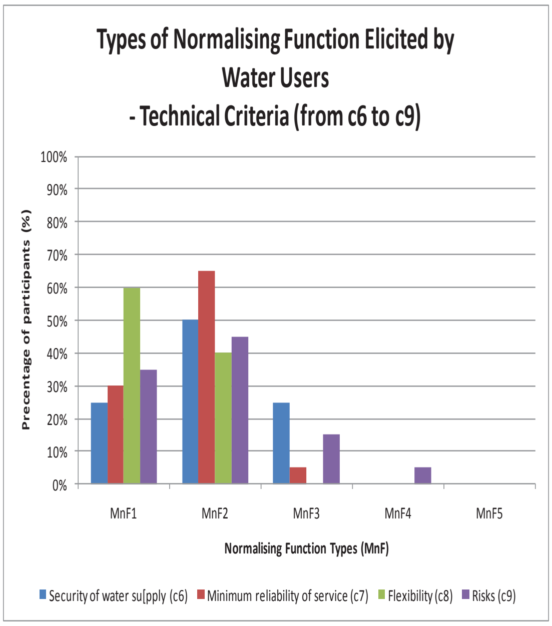


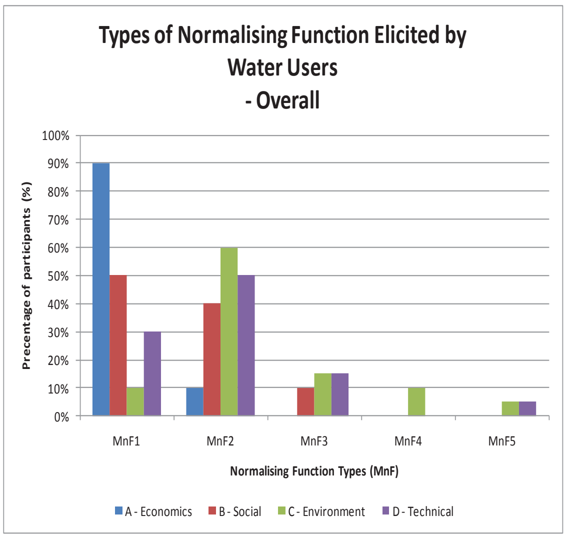



Types of Normalising Function Elicited by Water Users - Social (from c1 to c3)
Precentage of participants (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MnF1
MnF2
MnF3
MnF4
MnF5
Normalising Function Types (MnF)
Short-term construction impacts (c1)
Long-term community impacts (c2)
Likelihood of community acceptance (c3)


Types of Normalising Function Elicited by Water Users - Ecosystem (from c4a to c4d)
Precentage of participants (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MnF1
MnF2
MnF3
MnF4
MnF5
Normalising Function Types (MnF)
Forest (c4a)
Flora & Fauna (c4b)
Macro-invertebrates (c4c)
Marine (c4d)

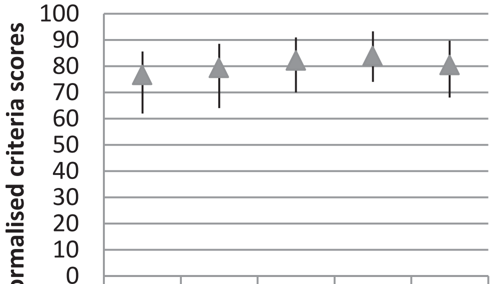

Types of Normalising Function Elicited by Water Users - Environment (from c4 to c5)
Precentage of participants (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MnF1
MnF2
MnF3
MnF4
MnF5
Normalising Function Types (MnF)
Loss of high value ecosystem (c4)
Greenhouse gas emissions (c5)


Types of Normalising Function Elicited by Water Users - Technical Criteria (from c6 to c9)
Precentage of participants (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MnF1
MnF2
MnF3
MnF4
MnF5
Normalising Function Types (MnF)
Security of water su[pply (c6)
Minimum reliability of service (c7)
Flexibility (c8)
Risks (c9)


Types of Normalising Function Elicited by Water Users - Overall
Precentage of participants (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MnF1
MnF2
MnF3
MnF4
MnF5
Normalising Function Types (MnF)
A - Economics
B - Social
C - Environment
D - Technical

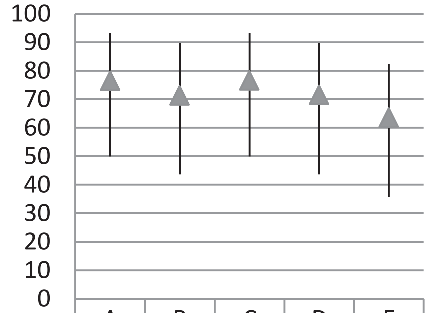
F2 Normalised criteria scores

Social: c1 Short-term construction impact



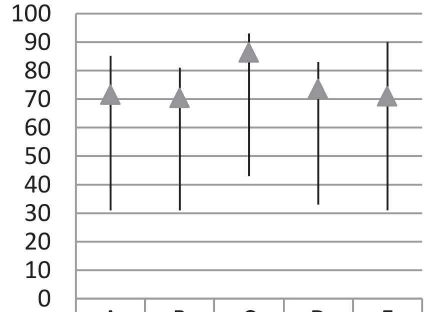
	A	B	C	D	E
Max	86	89	91	93	90
Min	62	64	70	74	68
▲ Average	77	79	82	84	80

Social: c2 Long-term impacts on local community



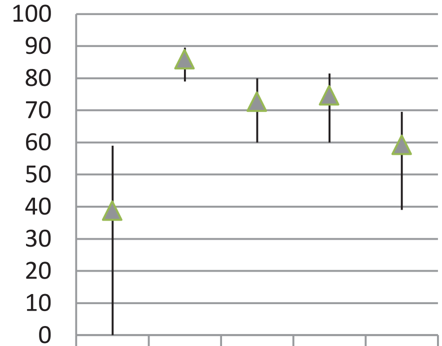
	A	B	C	D	E
Max	93	90	93	90	82
Min	50	44	50	44	36
▲ Average	76	71	77	72	64

Social: c3 Likelihood of community acceptance



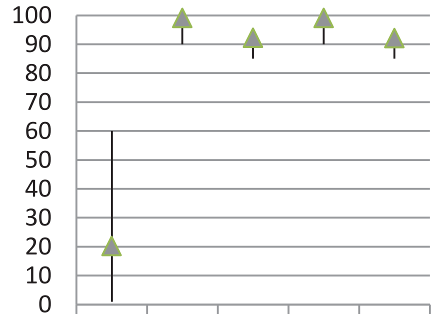
	A	B	C	D	E
Max	85	81	93	83	90
Min	31	31	43	33	31
▲ Average	72	70	86	74	71

Ecosystem: c4a Forest clearing



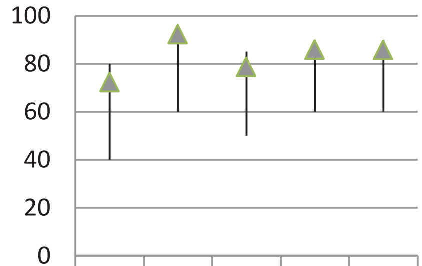
	A	B	C	D	E
Max	59	90	80	82	70
Min	0	79	60	60	39
▲ Average	39	86	73	75	59

Ecosystem: c4b Flora and Fauna



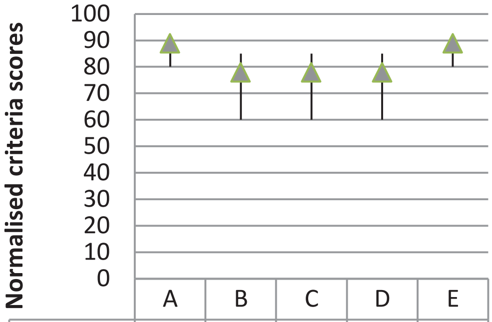
	A	B	C	D	E
Max	60	100	94	100	94
Min	1	90	85	90	85
▲ Average	20	99	92	99	92

Ecosystem: c4c Macroinvertebrates



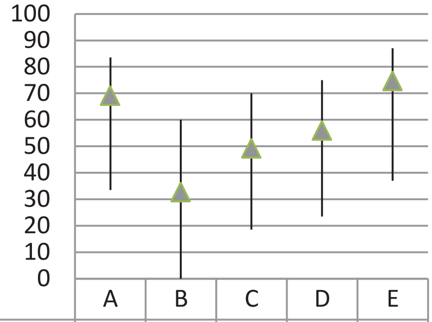
	A	B	C	D	E
Max	80	95	85	90	90
Min	40	60	50	60	60
▲ Average	72	92	79	86	86

Ecosystem: c4d Marine Organisms



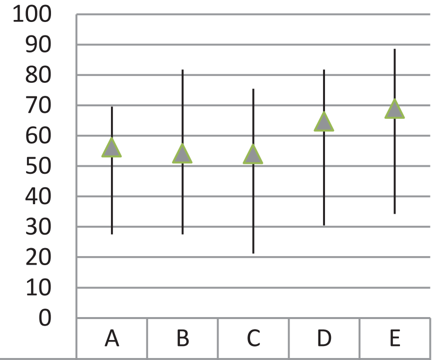
	A	B	C	D	E
Max	90	85	85	85	90
Min	80	60	60	60	80
▲ Average	89	78	78	78	89

Environment: c4 Loss of high value ecosystem



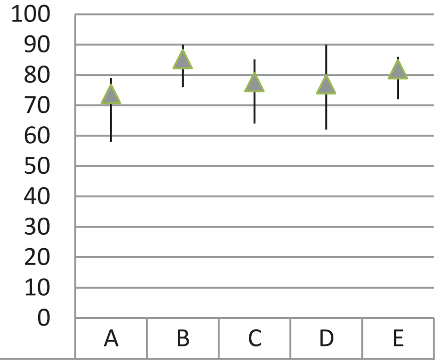
	A	B	C	D	E
Max	84	60	70	75	87
Min	34	0	19	24	37
▲ Average	69	33	49	56	75

Technical: c6 Security of supply



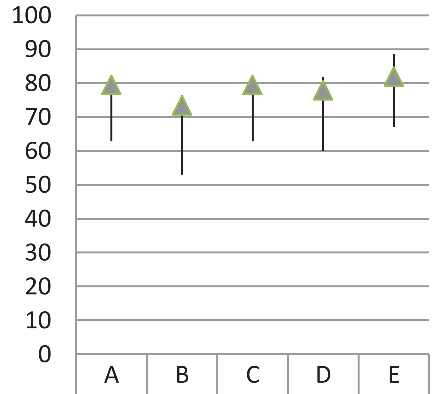
	A	B	C	D	E
Max	70	82	75	82	89
Min	27	27	21	30	34
▲ Average	56	54	54	65	69

Technical: c7 Reliability



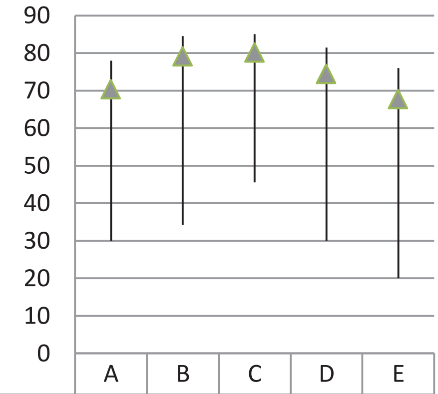
	A	B	C	D	E
Max	79	90	85	90	86
Min	58	76	64	62	72
▲ Average	74	85	78	77	82

Technical: c8 Flexibility



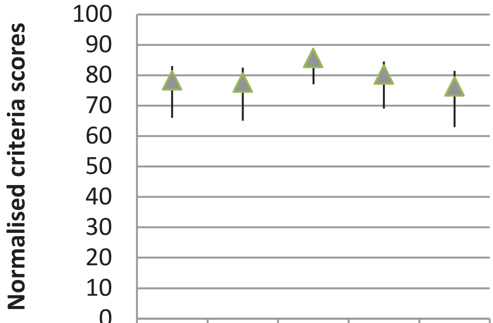
	A	B	C	D	E
Max	82	77	82	82	89
Min	63	53	63	60	67
▲ Average	79	73	79	78	82

Technical: c9 Risk



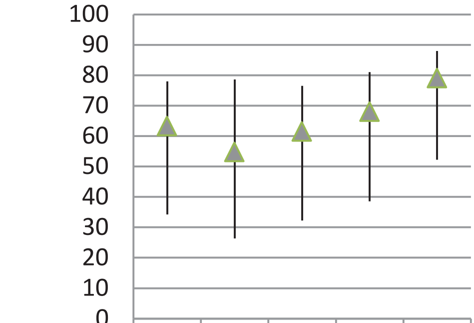
	A	B	C	D	E
Max	78	85	85	82	76
Min	30	34	46	30	20
▲ Average	70	79	80	74	68

Overall: Social



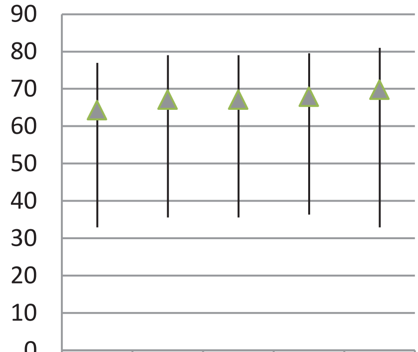
	A	B	C	D	E
Max	83	83	89	85	82
Min	66	65	77	69	63
▲ Average	78	78	86	80	76

Overall: Environment



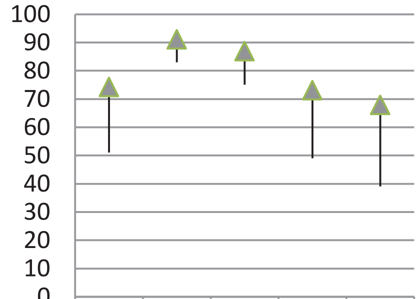
	A	B	C	D	E
Max	78	79	77	81	88
Min	34	26	32	39	52
▲ Average	63	55	61	68	79

Overall: Technical



	A	B	C	D	E
Max	77	79	79	80	81
Min	33	36	36	36	33
▲ Average	64	67	67	68	70

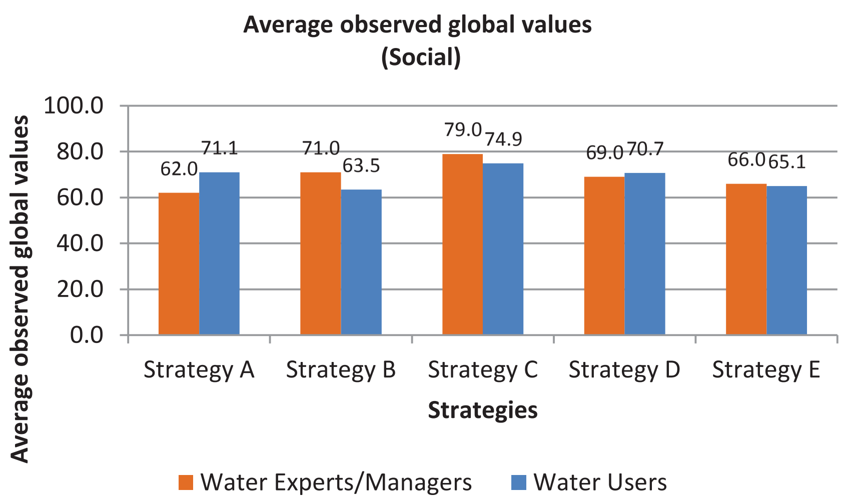
Overall: c10 Whole-of-life-cost (Economic)



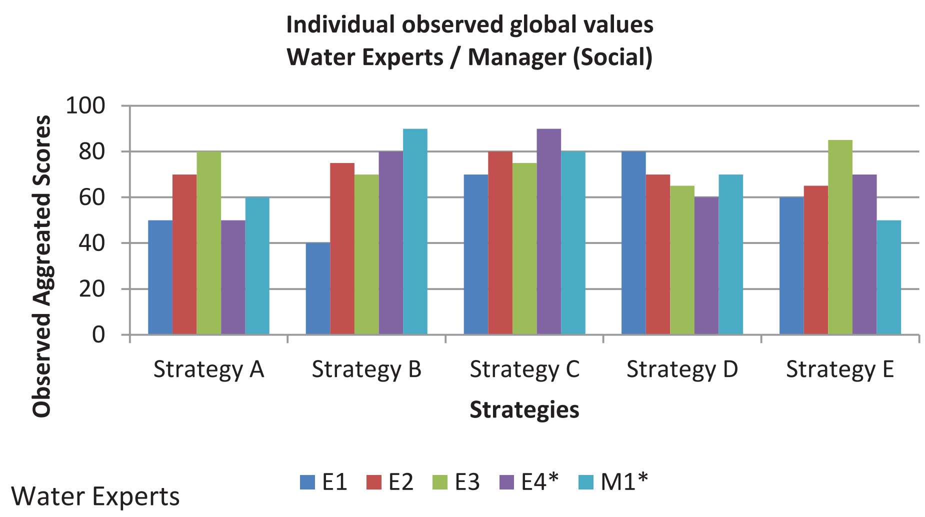
	A	B	C	D	E
Max	76	92	88	75	70
Min	51	83	75	49	39
▲ Average	74	91	87	73	68

F3 Observed global values

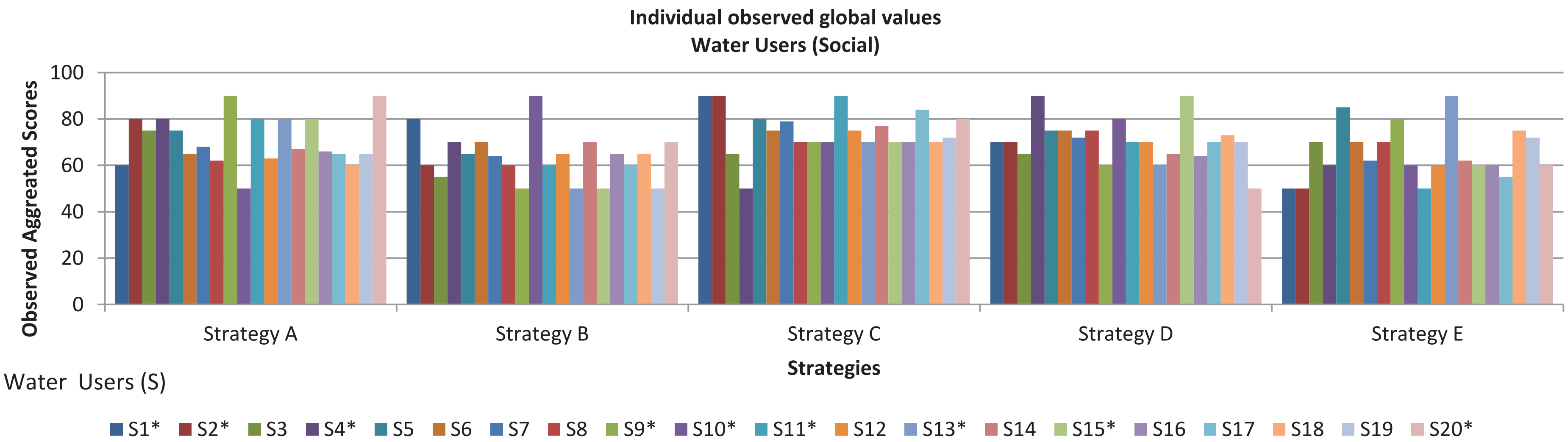
Social



Average observed global values (Social)
Average observed global values
100.0
80.0
60.0
40.0
20.0
0.0
62.0
71.1
71.0
63.5
79.0
74.9
69.0
70.7
66.0
65.1
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Experts/Managers
Water Users

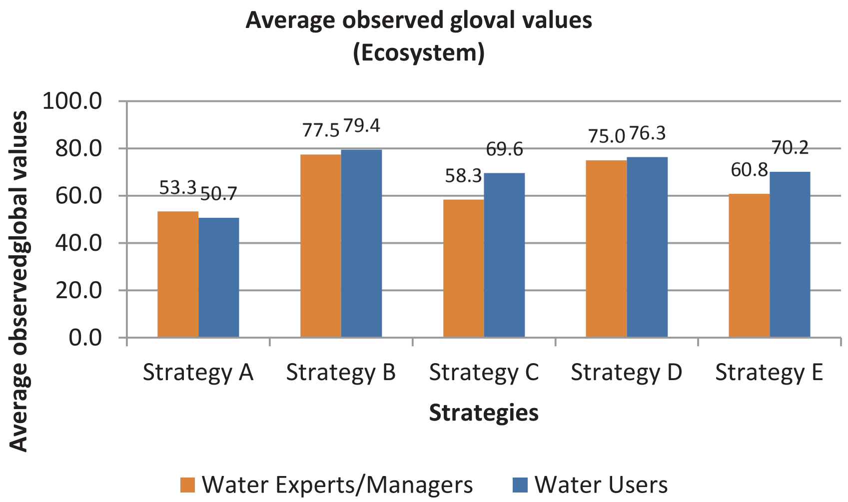


Individual observed global values
Water Experts / Manager (Social)
Observed Aggreated Scores
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Experts
E1
E2
E3
E4*
M1*

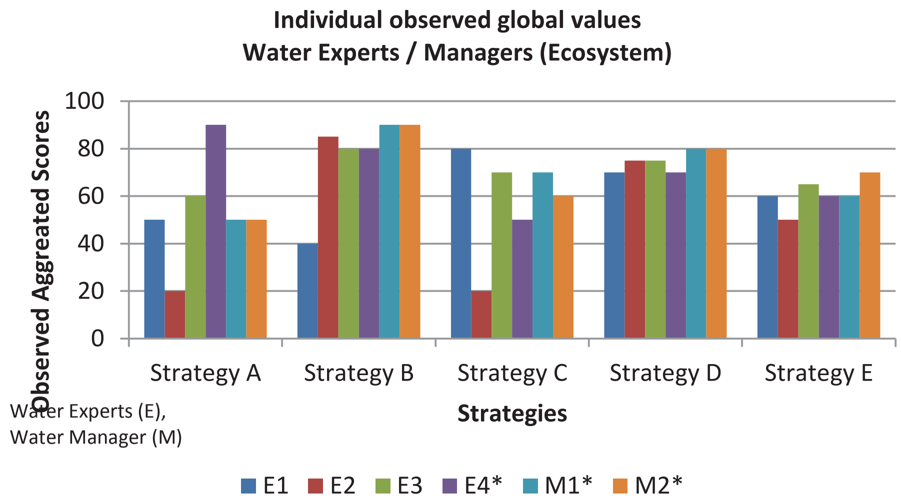


Individual observed global values
Water Users (Social)
Observed Aggreated Scores
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Users (S)
S1*
S2*
S3
S4*
S5
S6
S7
S8
S9*
S10*
S11*
S12
S13*
S14
S15*
S16
S17
S18
S19
S20*

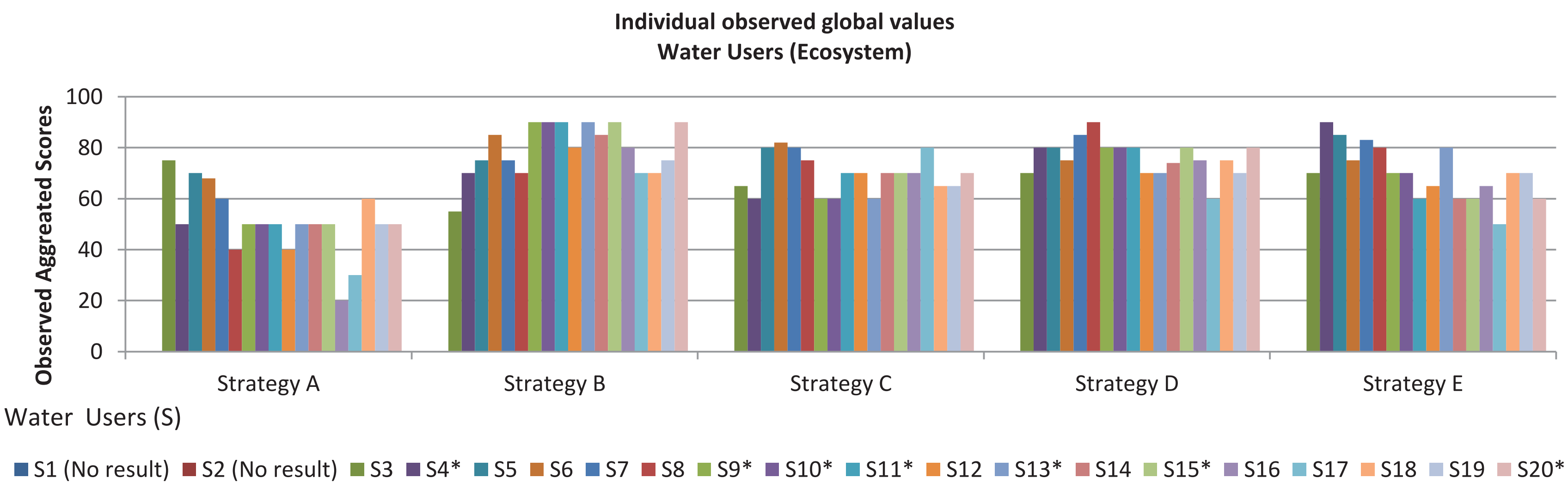
Ecosystem



Average observed gloval values
(Ecosystem)
Average observedglobal values
100.0
80.0
60.0
40.0
20.0
0.0
53.3
50.7
77.5
79.4
58.3
69.6
75.0
76.3
60.8
70.2
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Experts/Managers
Water Users

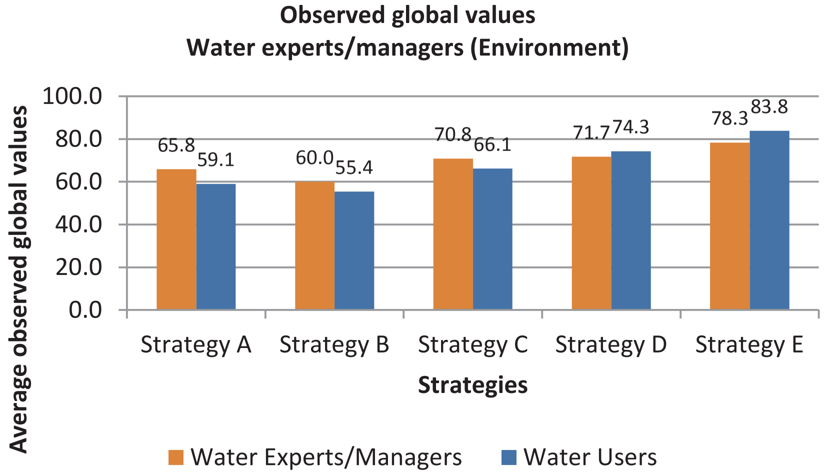


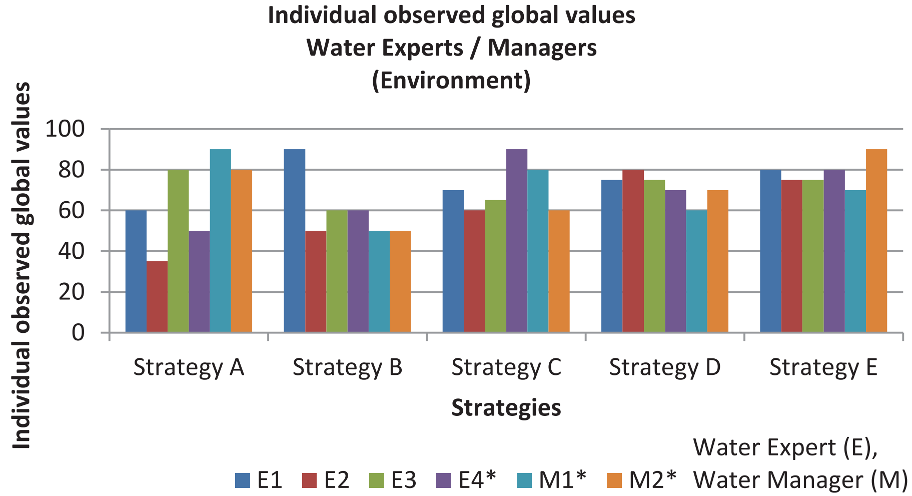
Individual observed global values
Water Experts / Managers (Ecosystem)
Observed Aggreated Scores
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Experts (E),
Water Manager (M)
E1
E2
E3
E4*
M1*
M2*

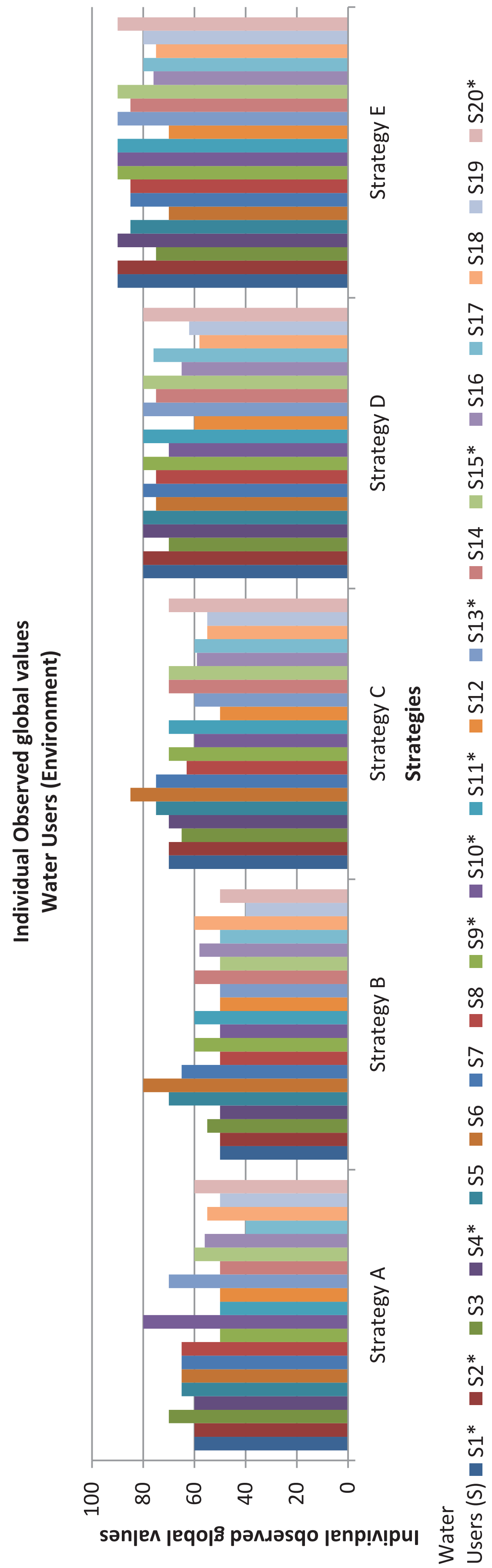


Individual observed global values
Water Users (Ecosystem)
Observed Aggreated Scores
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Water Users (S)
S1 (No result)
S2 (No result)
S3
S4*
S5
S6
S7
S8
S9*
S10*
S11*
S12
S13*
S14
S15*
S16
S17
S18
S19
S20*

Environment

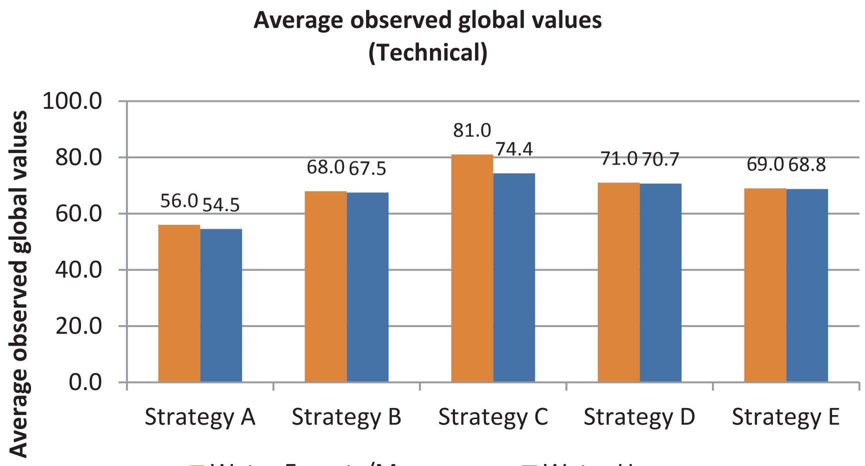


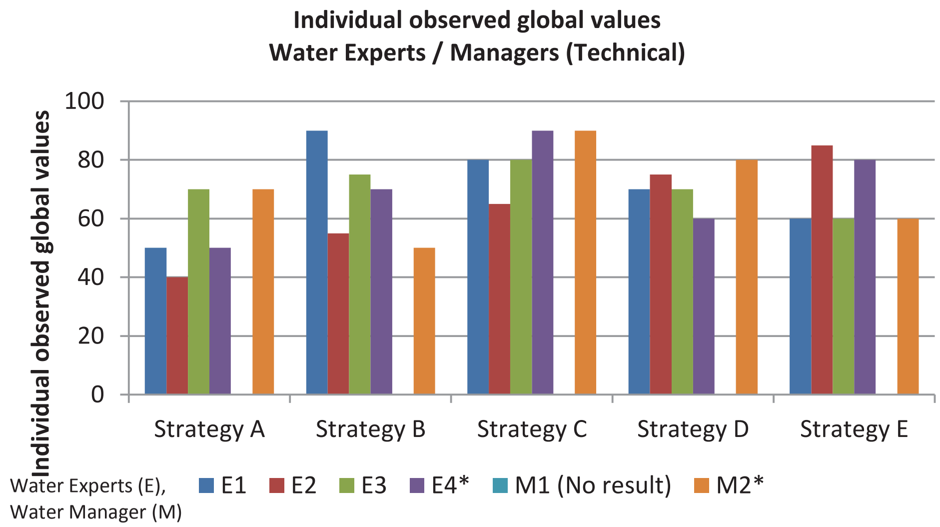


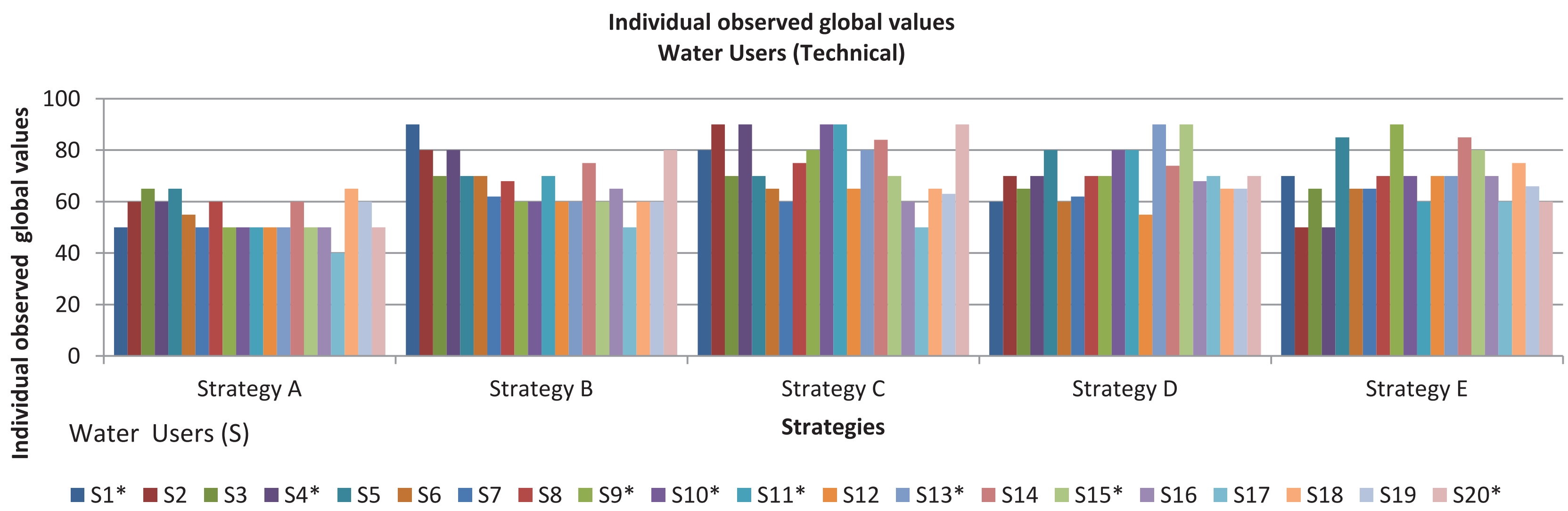


Individual Observed global values
Water Users (Environment)
Individual observed global values
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Users (S)
S1*
S2*
S3
S4*
S5
S6
S7
S8
S9*
S10*
S11*
S12
S13*
S14
S15*
S16
S17
S18
S19
S20*

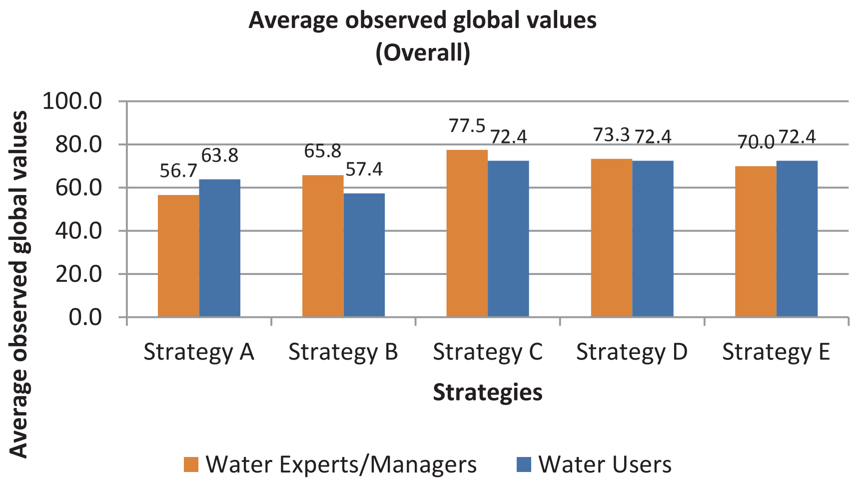
Technical

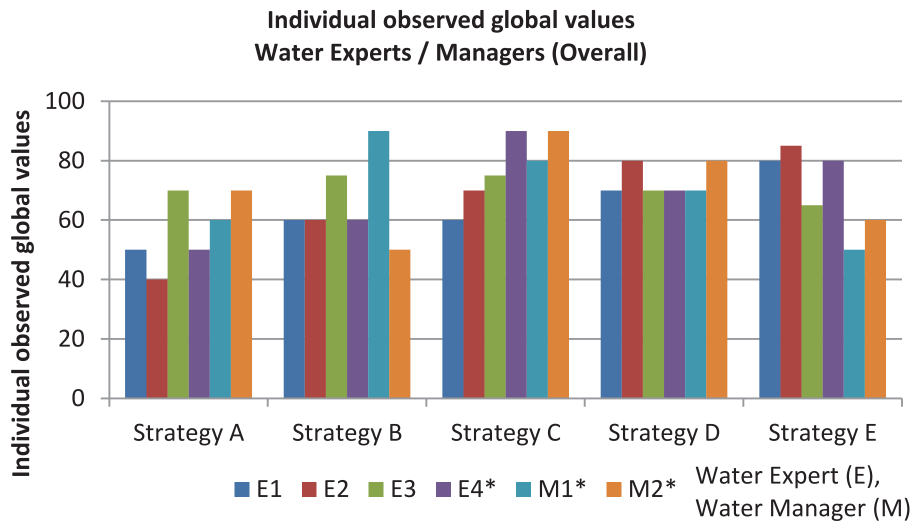

Average observed global values
(Technical)
Average observed global values
100.0
80.0
60.0
40.0
20.0
0.0
56.0
54.5
68.0
67.5
81.0
74.4
71.0
70.7
69.0
68.8
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Water Experts/Managers
Water Users

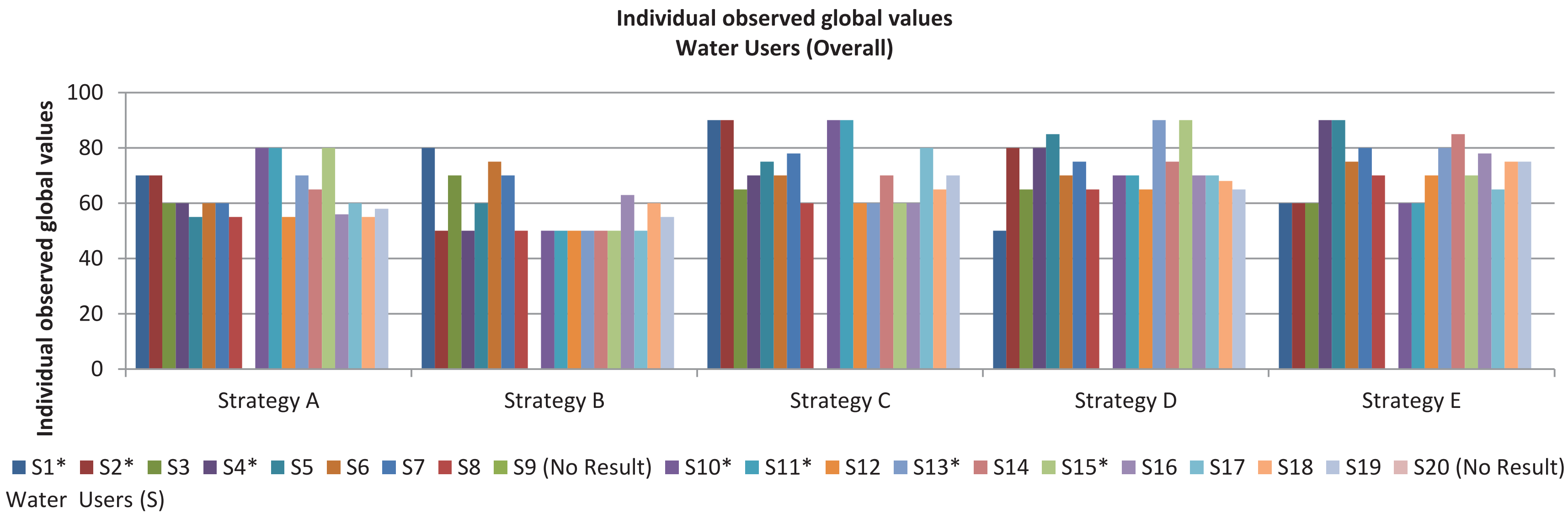

Individual observed global values
Water Experts / Managers (Technical)
Individual observed global values
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Water Experts (E),
Water Manager (M)
E1
E2
E3
E4*
M1 (No result)
M2*


Individual observed global values
Water Users (Technical)
Individual observed global values
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Water Users (S)
Strategies
S1*
S2
S3
S4*
S5
S6
S7
S8
S9*
S10*
S11*
S12
S13*
S14
S15*
S16
S17
S18
S19
S20*

Overall

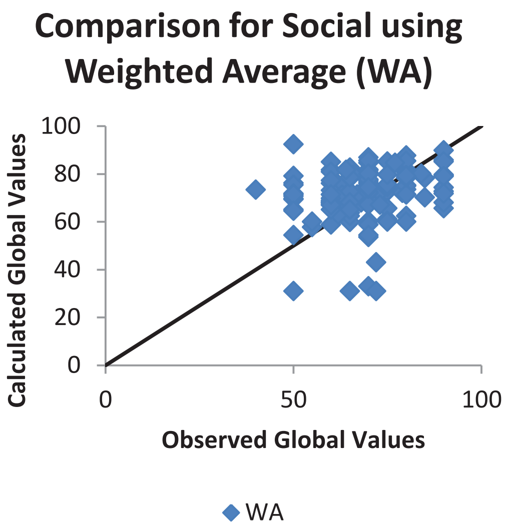

Average observed global values
(Overall)
Average observed global values
100.0
80.0
60.0
40.0
20.0
0.0
56.7
63.8
65.8
57.4
77.5
72.4
73.3
72.4
70.0
72.4
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
Strategies
Water Experts/Managers
Water Users

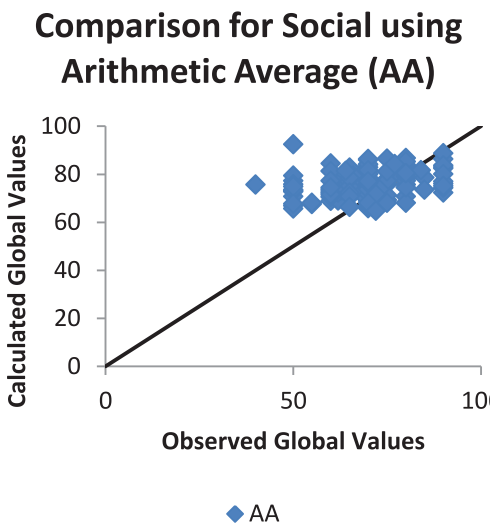

Individual observed global values
Water Experts / Managers (Overall)
Individual observed global values
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
E1
E2
E3
E4*
M1*
M2*
Water Expert (E),
Water Manager (M)

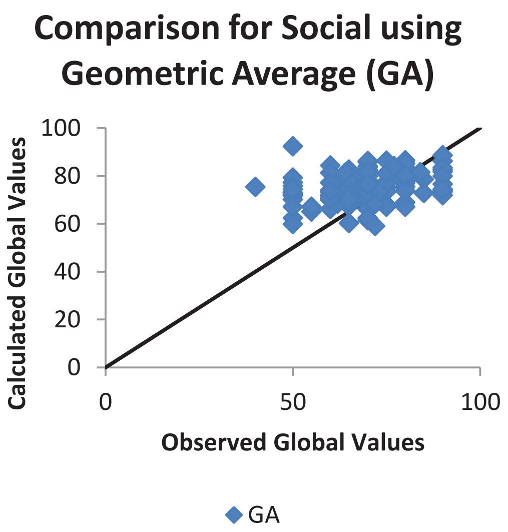

Individual observed global values
Water Users (Overall)
Individual observed global values
100
80
60
40
20
0
Strategy A
Strategy B
Strategy C
Strategy D
Strategy E
S1* S2* S3 S4* S5 S6 S7 S8 S9 (No Result) S10* S11* S12 S13* S14 S15* S16 S17 S18 S19 S20 (No Result)
Water Users (S)

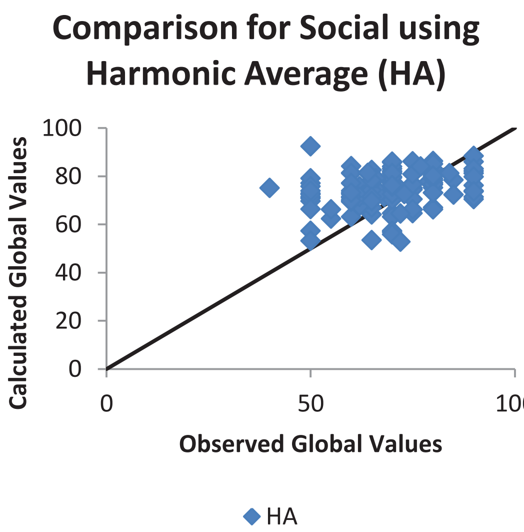
F4 Calculated global values vs. Observed global values scatterplots

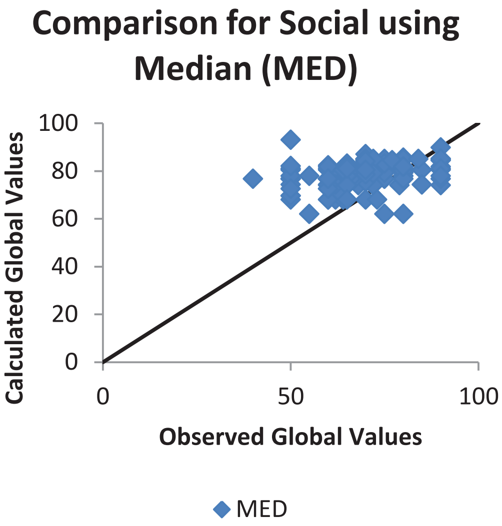
Social

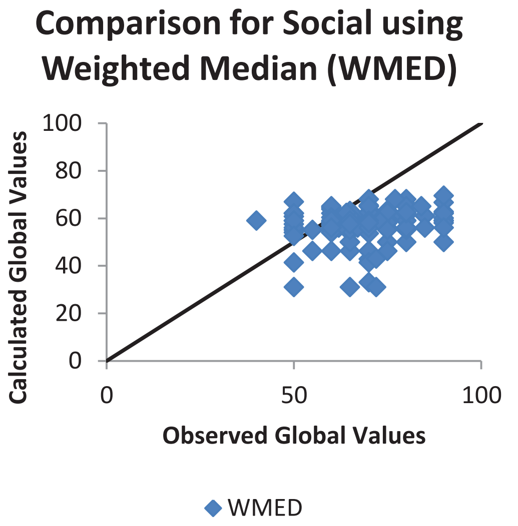


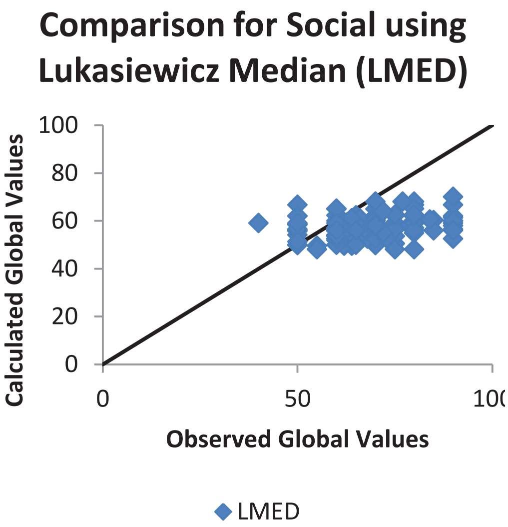


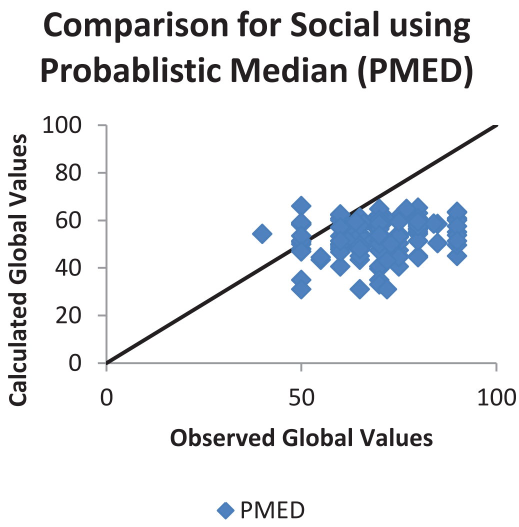


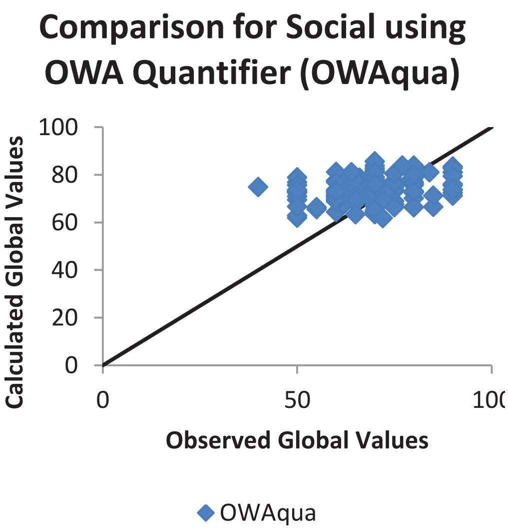


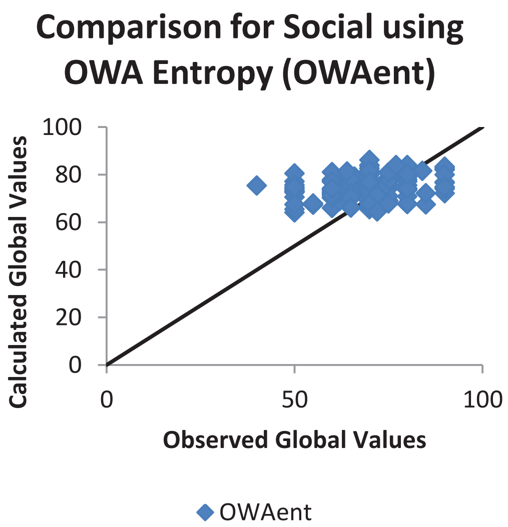

Comparison for Social using
Median (MED)
Calculated Global Values
Observed Global Values
MED

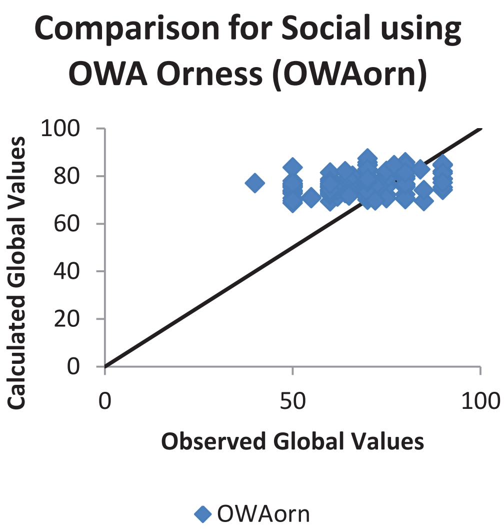

Comparison for Social using
Weighted Median (WMED)
Calculated Global Values
Observed Global Values
WMED

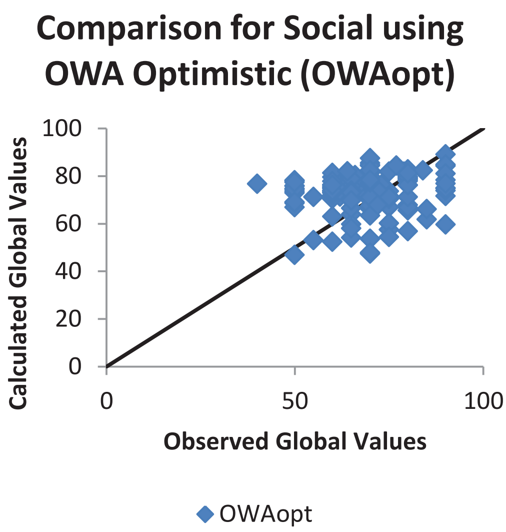

Comparison for Social using
Lukasiewicz Median (LMED)
Calculated Global Values
Observed Global Values
LMED

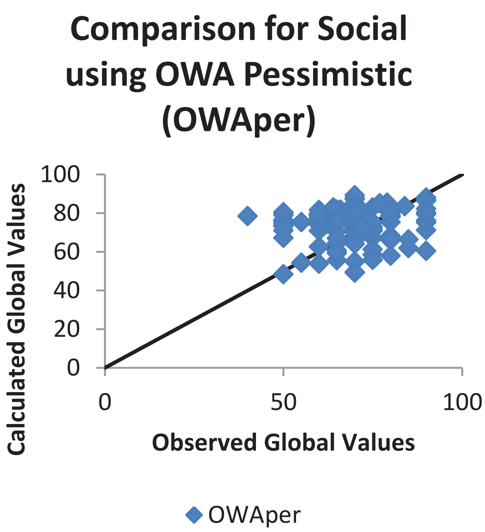

Comparison for Social using
Probablistic Median (PMED)
Calculated Global Values
Observed Global Values
PMED

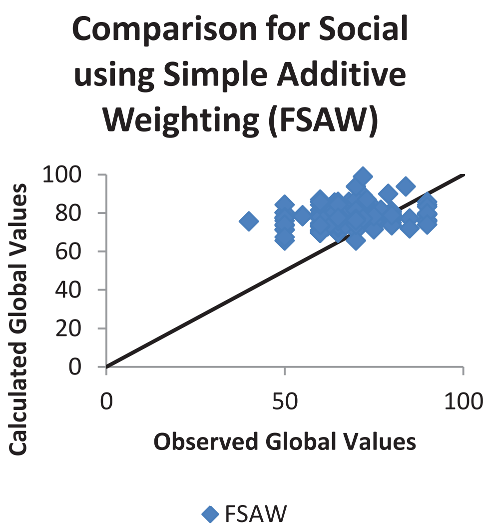

Comparison for Social using
OWA Quantifier (OWAqua)
Calculated Global Values
Observed Global Values
OWAqua


Comparison for Social using
OWA Entropy (OWAent)
Calculated Global Values
Observed Global Values
OWAent

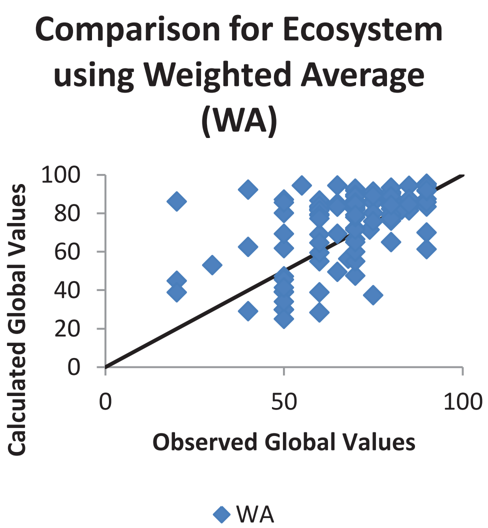

Comparison for Social using OWA Orness (OWAorn)
Calculated Global Values
Observed Global Values
OWAorn

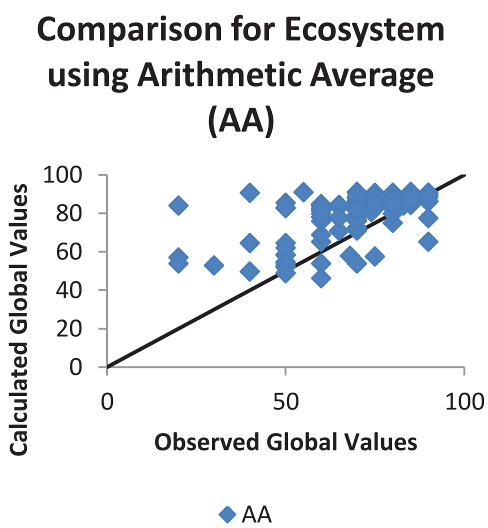

Comparison for Social using OWA Optimistic (OWAopt)
Calculated Global Values
Observed Global Values
OWAopt

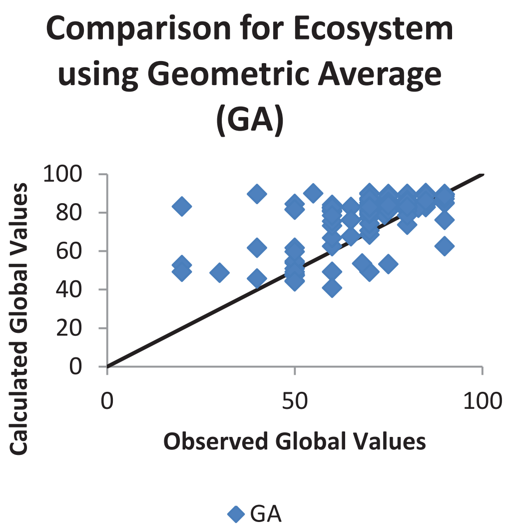

Comparison for Social using OWA Pessimistic (OWAper)
Calculated Global Values
Observed Global Values
OWAper

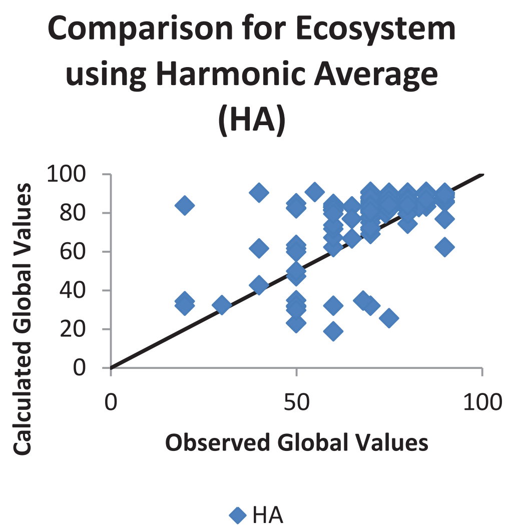

Comparison for Social using Simple Additive Weighting (FSAW)
Calculated Global Values
Observed Global Values
FSAW

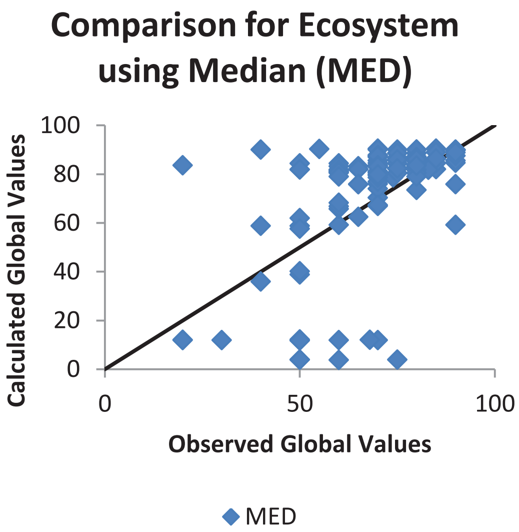
Ecosystem

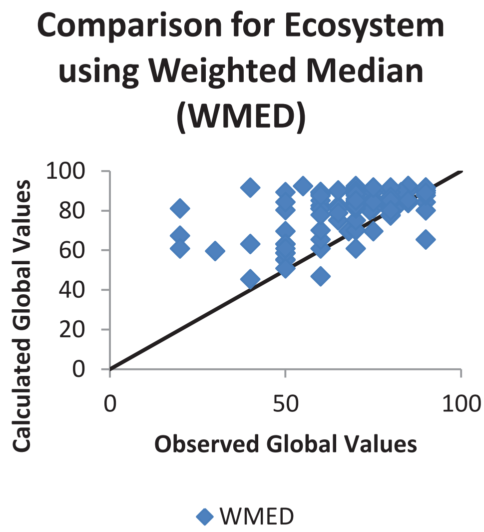

Comparison for Ecosystem using Weighted Average (WA)
Calculated Global Values
Observed Global Values
WA

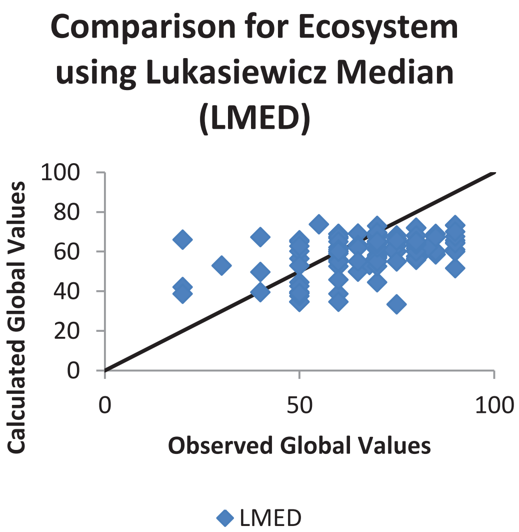

Comparison for Ecosystem using Arithmetic Average (AA)
Calculated Global Values
Observed Global Values
AA

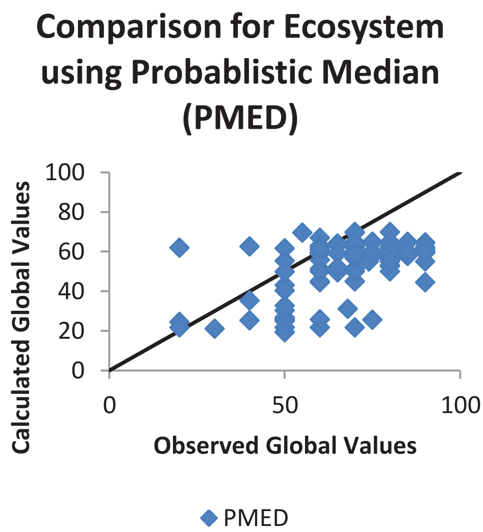

Comparison for Ecosystem using Geometric Average (GA)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
GA

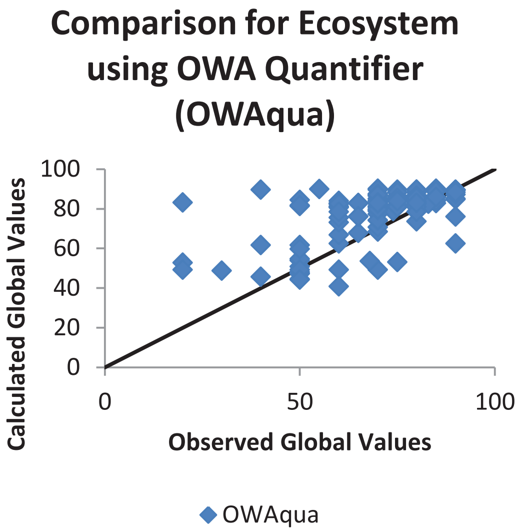

Comparison for Ecosystem using Harmonic Average (HA)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
HA

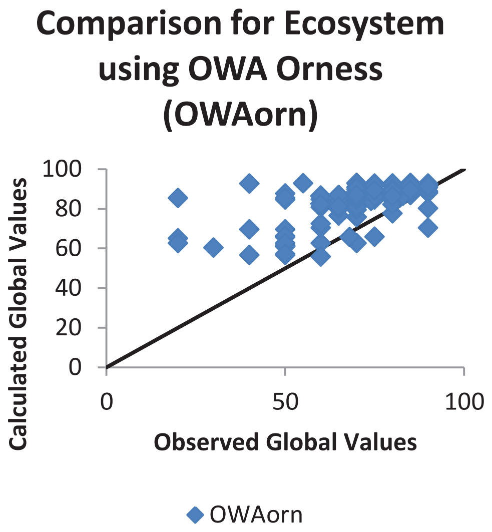

Comparison for Ecosystem using Median (MED)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
MED

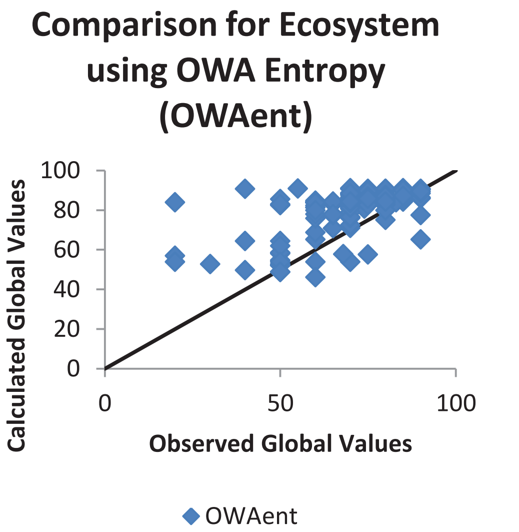

Comparison for Ecosystem using Weighted Median (WMED)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
WMED

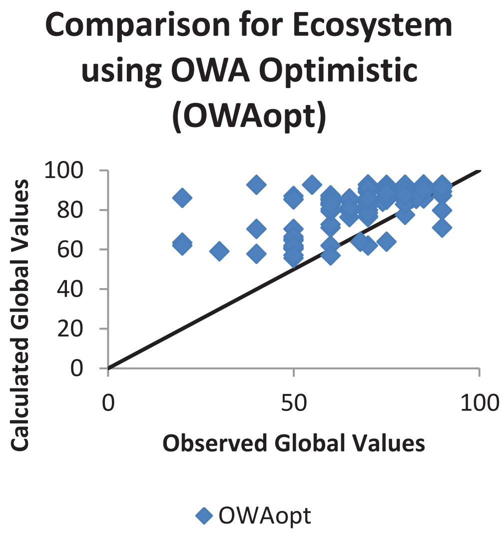

Comparison for Ecosystem using Lukasiewicz Median (LMED)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
LMED

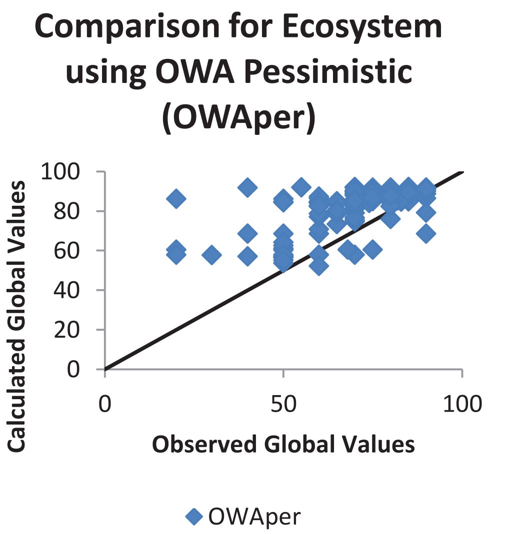

Comparison for Ecosystem using Probablistic Median (PMED)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
PMED

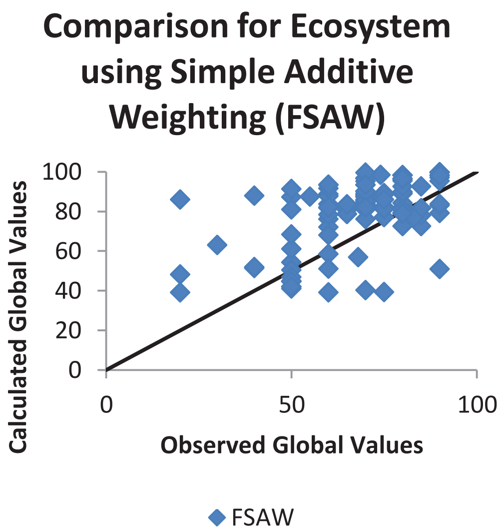

Comparison for Ecosystem using OWA Quantifier (OWAqua)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAqua


Comparison for Ecosystem using OWA Orness (OWAorn)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAorn

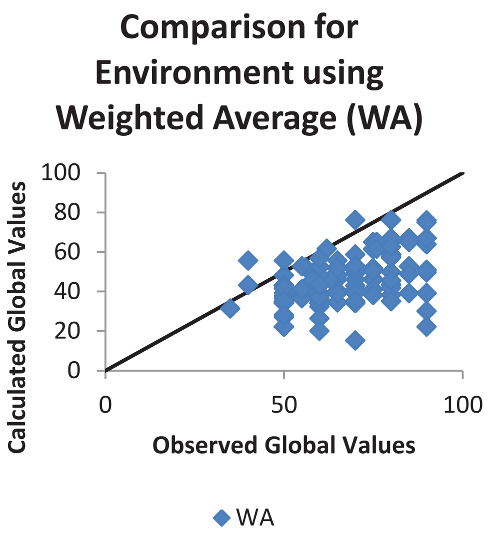

Comparison for Ecosystem using OWA Entropy (OWAent)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAent

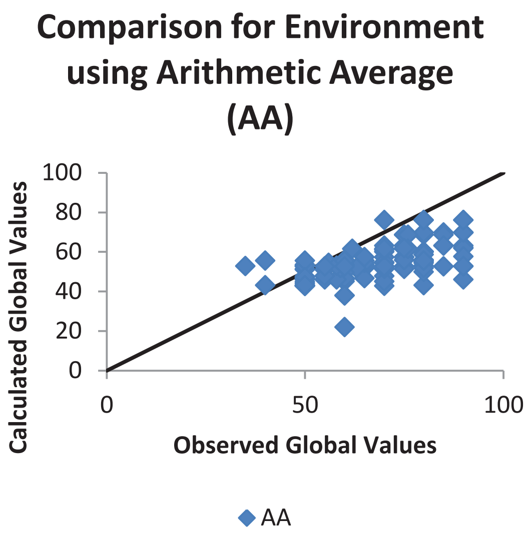

Comparison for Ecosystem using OWA Optimistic (OWAopt)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAopt

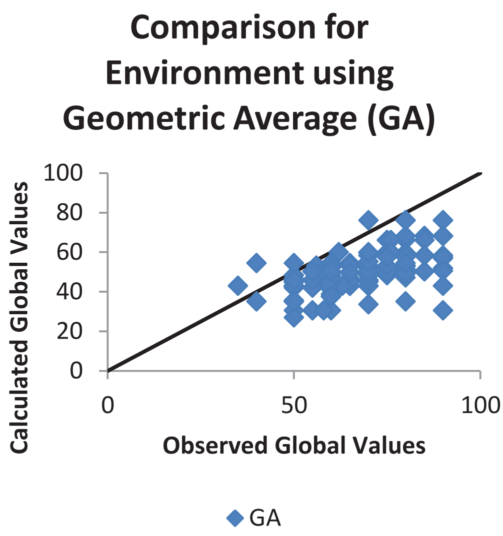

Comparison for Ecosystem using OWA Pessimistic (OWAper)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAper

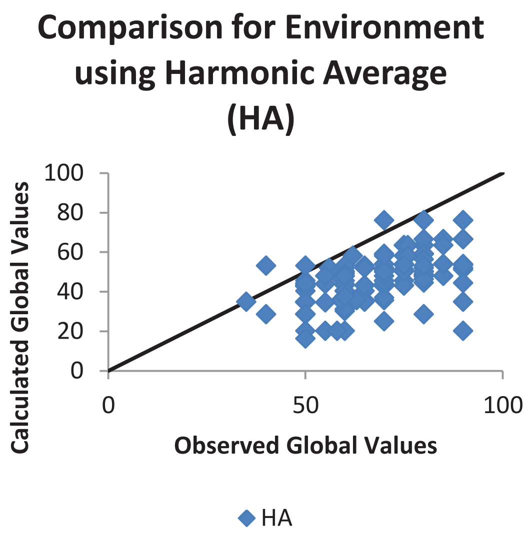

Comparison for Ecosystem using Simple Additive Weighting (FSAW)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
FSAW

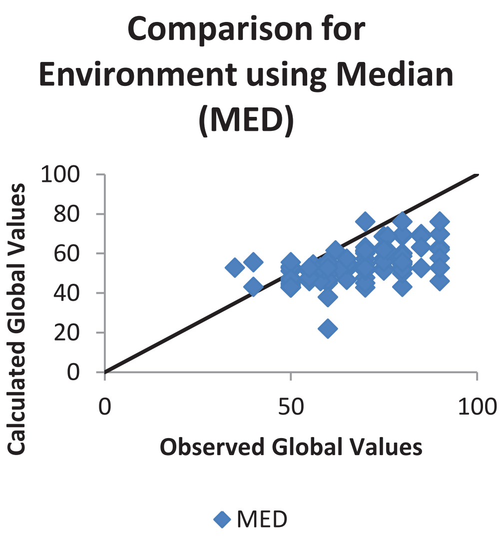
Environment

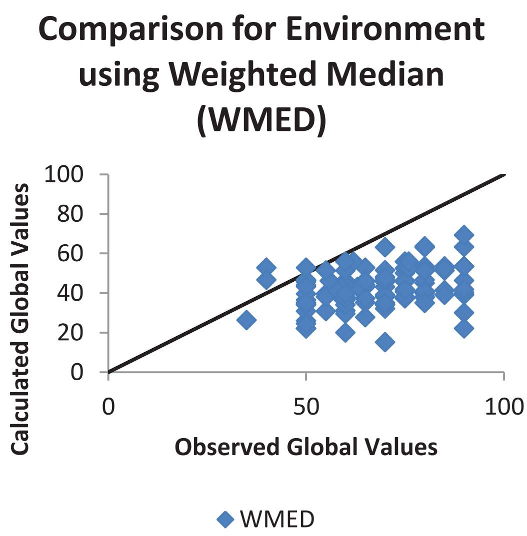


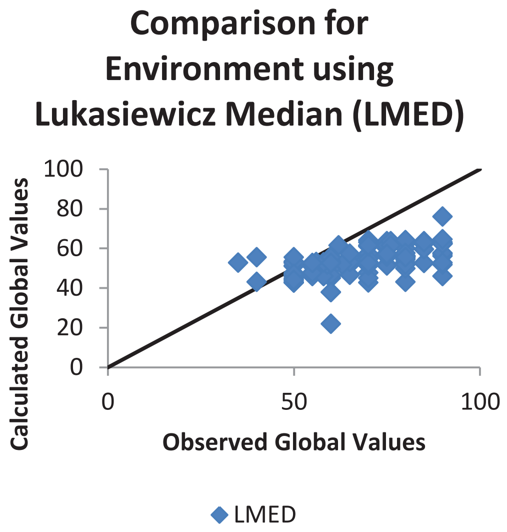


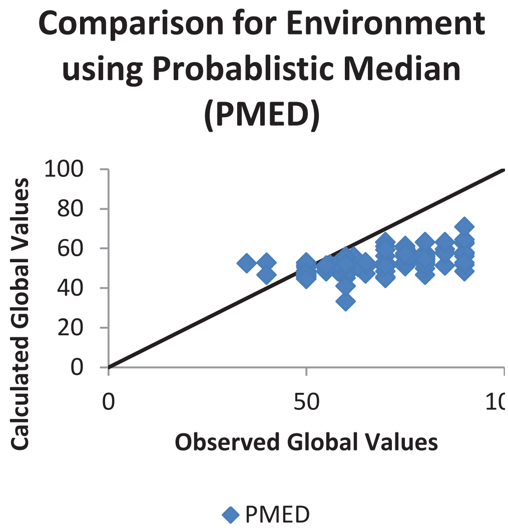









Comparison for Environment using Lukasiewicz Median (LMED)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
LMED


Comparison for Environment using Probablistic Median (PMED)
Calculated Global Values
Observed Global Values
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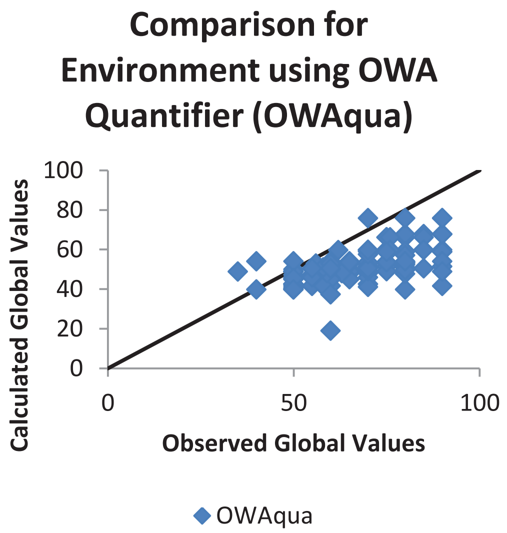
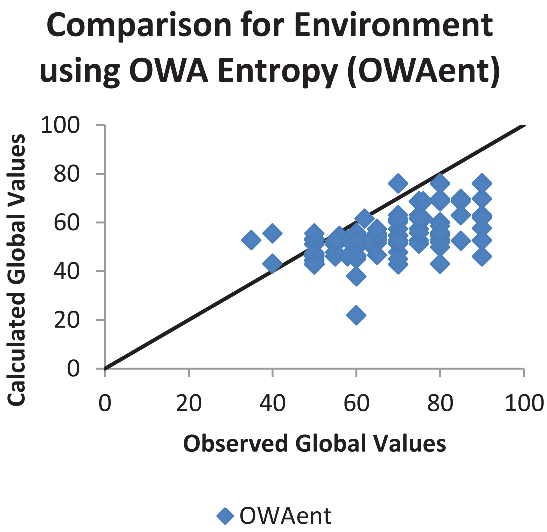
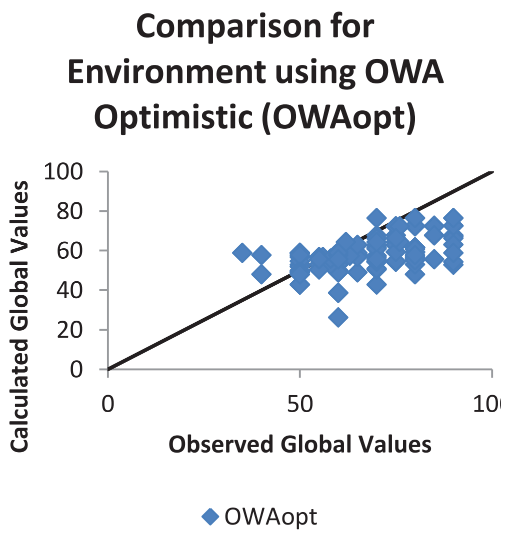
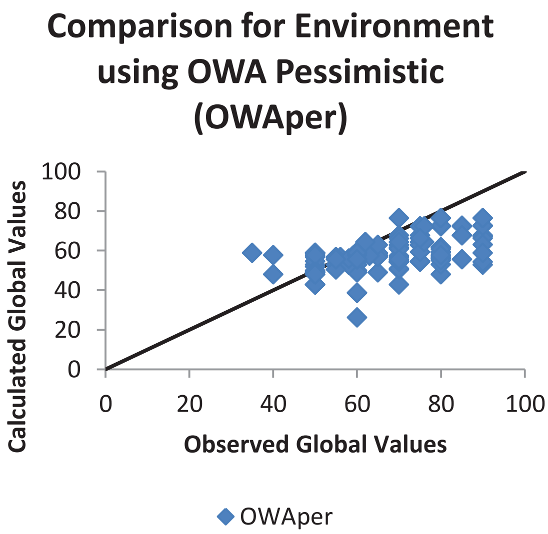
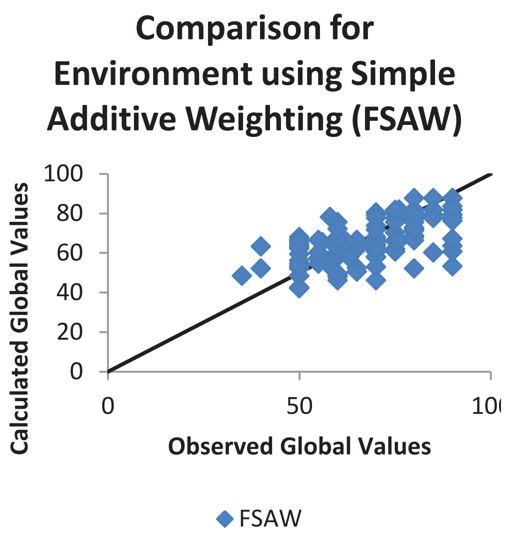
20
40
60
80
100
0
50
PMED


Comparison for Environment using OWA Quantifier (OWAqua)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAqua

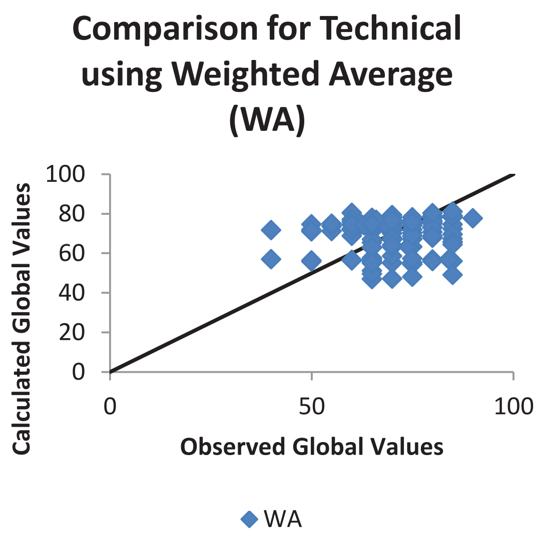

Comparison for Environment using OWA Entropy (OWAent)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
20
40
60
80
100
OWAent

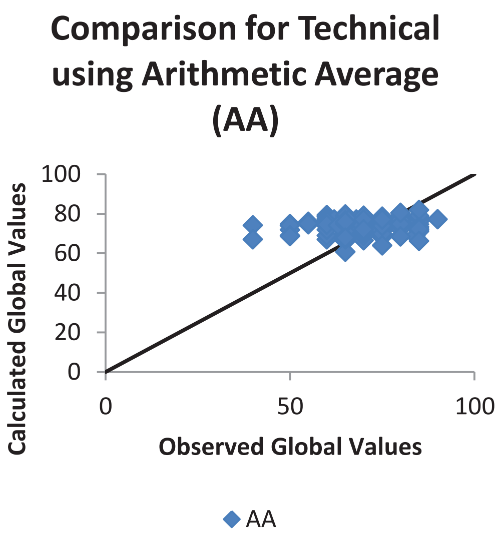

Comparison for Environment using OWA Optimistic (OWAopt)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
OWAopt

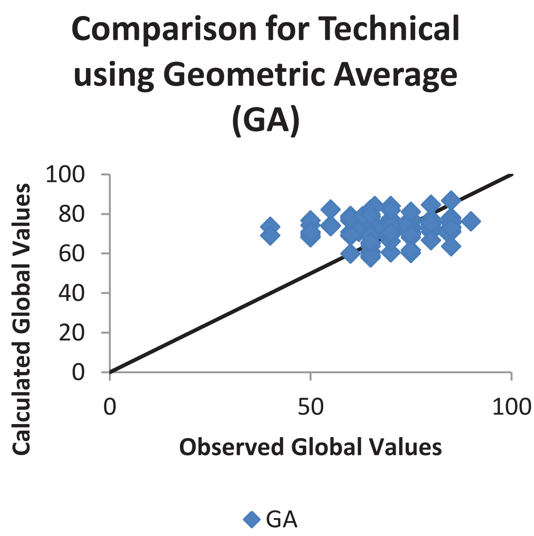

Comparison for Environment using OWA Pessimistic (OWAper)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
20
40
60
80
100
OWAper

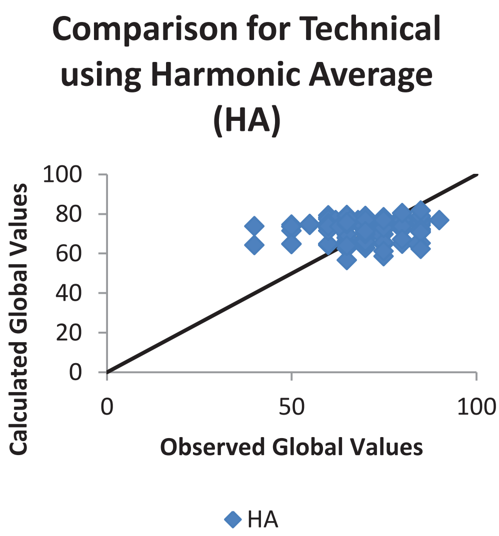

Comparison for Environment using Simple Additive Weighting (FSAW)
100
80
60
40
20
0
Calculated Global Values
0
50
10
Observed Global Values
FSAW

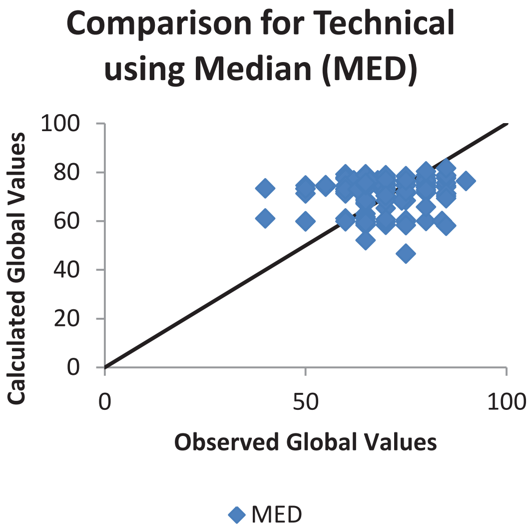
Technical

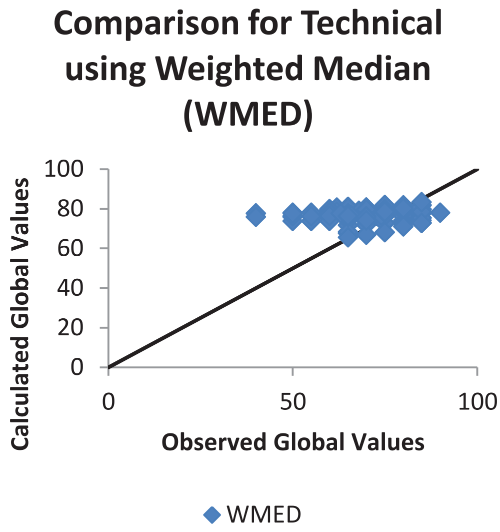

Comparison for Technical using Weighted Average (WA)
100
80
60
40
20
0
Calculated Global Values
0
50
100
Observed Global Values
WA

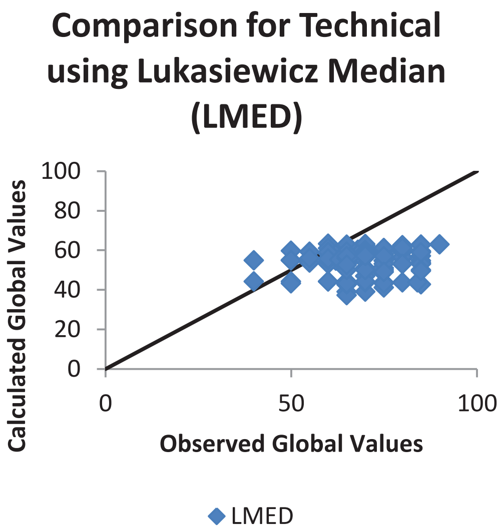

Comparison for Technical using Arithmetic Average (AA)
100
80
60
40
20
0
Calculated Global Values
0
50
100
Observed Global Values
AA

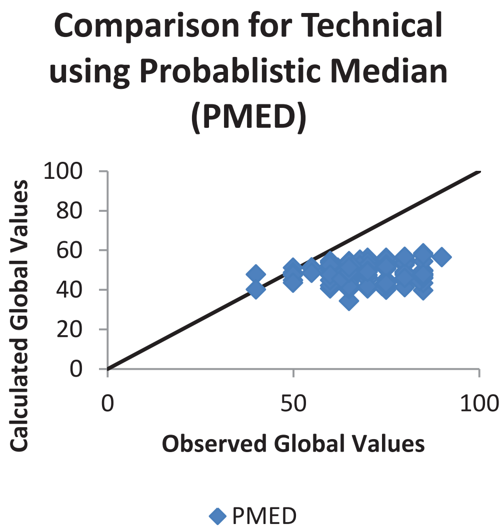

Comparison for Technical using Geometric Average (GA)
100
80
60
40
20
0
Calculated Global Values
0
50
100
Observed Global Values
GA

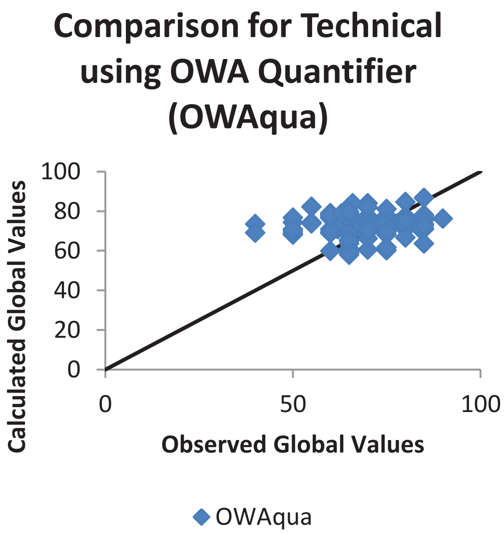

Comparison for Technical using Harmonic Average (HA)
100
80
60
40
20
0
Calculated Global Values
0
50
100
Observed Global Values
HA

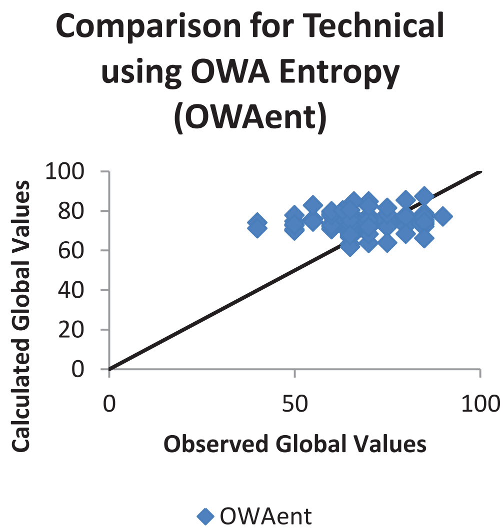

Comparison for Technical using Median (MED)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
MED

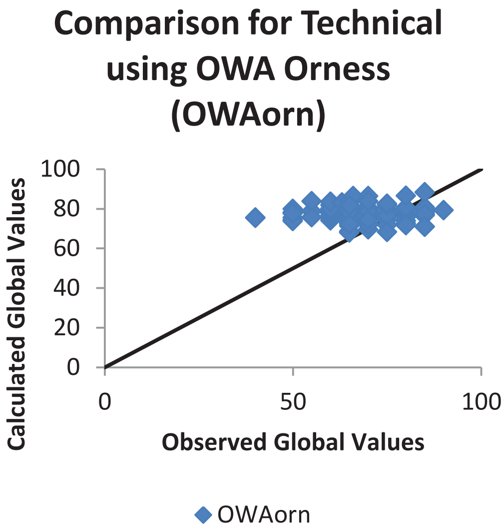

Comparison for Technical using Weighted Median (WMED)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
WMED

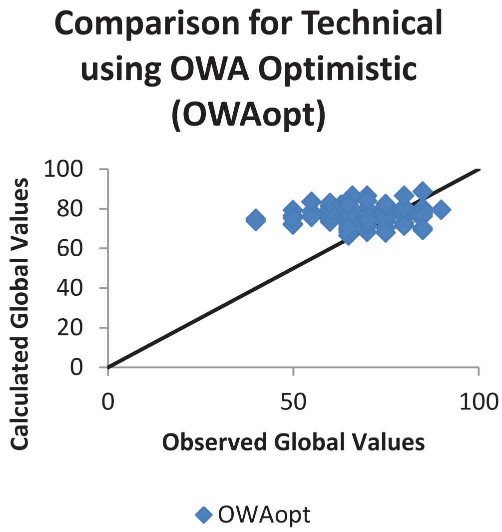

Comparison for Technical using Lukasiewicz Median (LMED)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
LMED

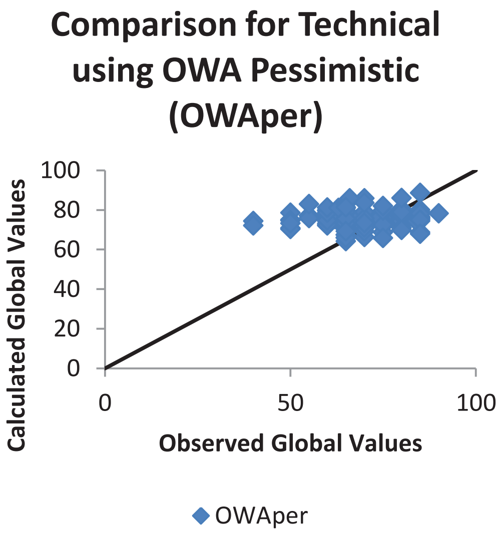

Comparison for Technical using Probablistic Median (PMED)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
PMED

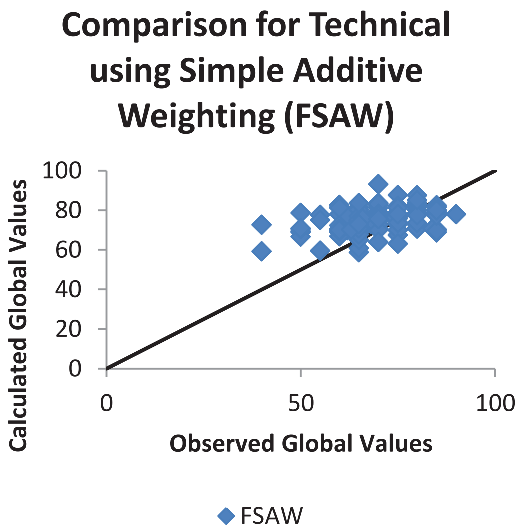

Comparison for Technical using OWA Quantifier (OWAqua)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
OWAqua


Comparison for Technical using OWA Entropy (OWAent)
Calculated Global Values
100
80
60
40
20
0
0
50
100
Observed Global Values
OWAent

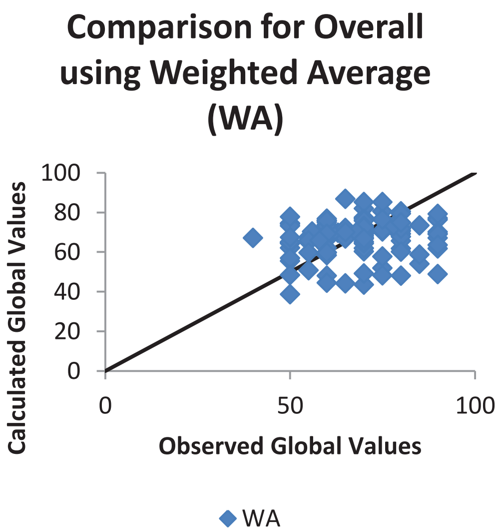

Comparison for Technical using OWA Orness (OWAorn)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
OWAorn

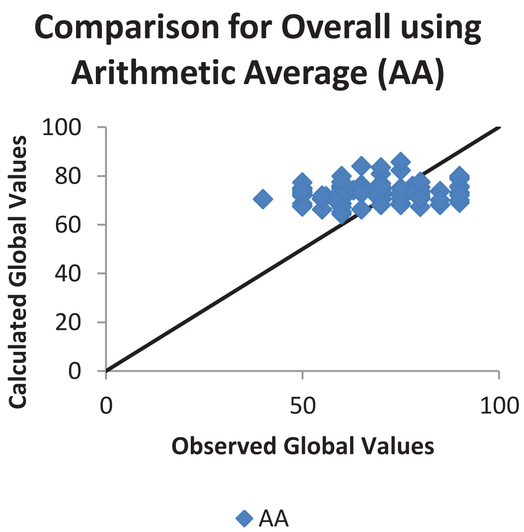

Comparison for Technical using OWA Optimistic (OWAopt)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
OWAopt

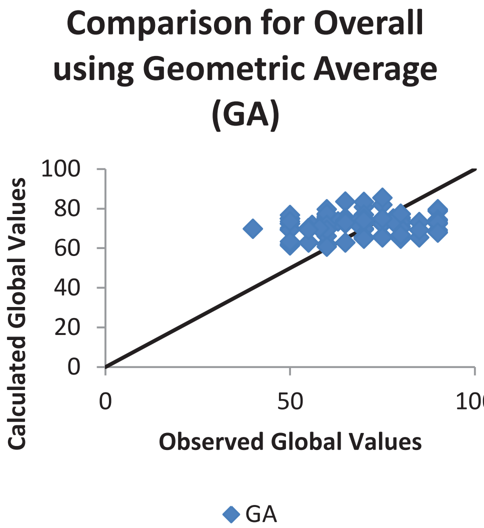

Comparison for Technical using OWA Pessimistic (OWAper)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
OWAper

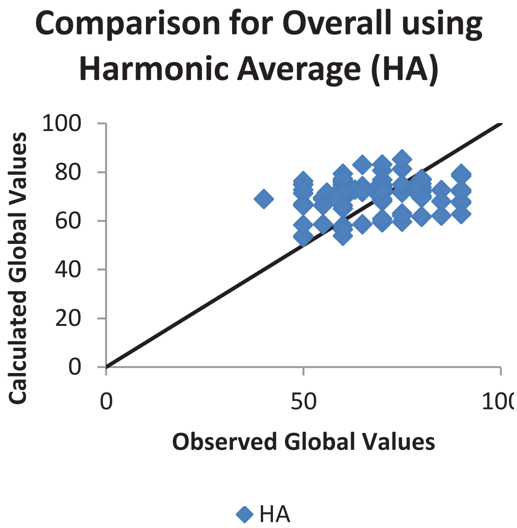

Comparison for Technical using Simple Additive Weighting (FSAW)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
FSAW

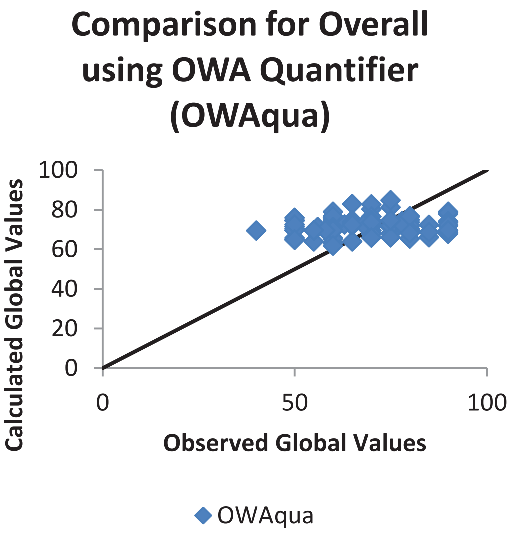
Overall

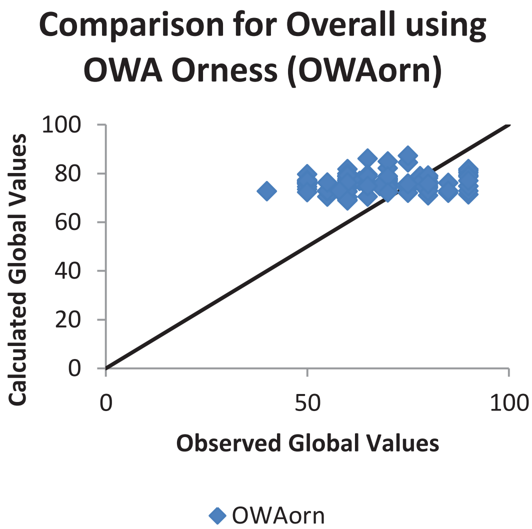

Comparison for Overall using Weighted Average (WA)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
WA

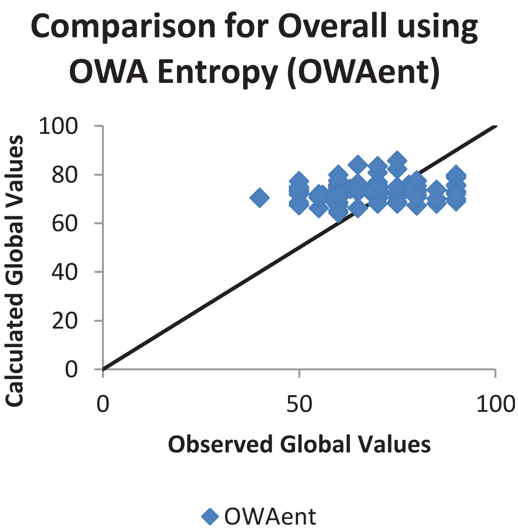

Comparison for Overall using Arithmetic Average (AA)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
AA

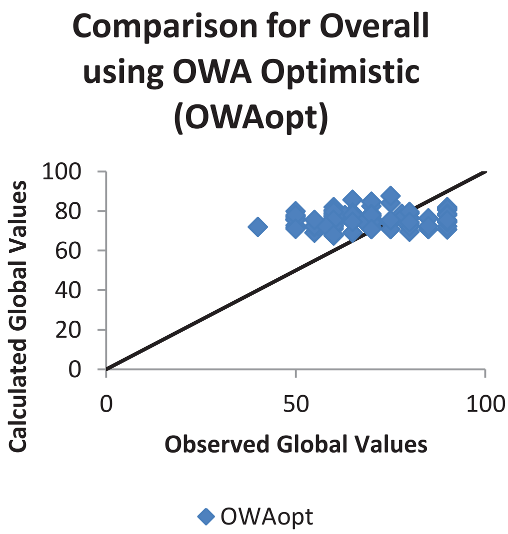

Comparison for Overall using Geometric Average (GA)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
GA

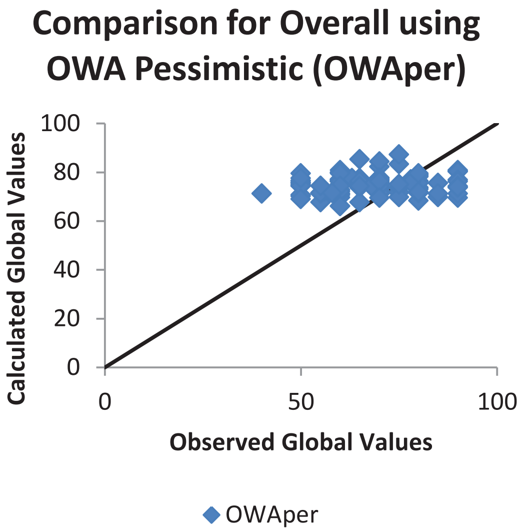

Comparison for Overall using Harmonic Average (HA)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
HA

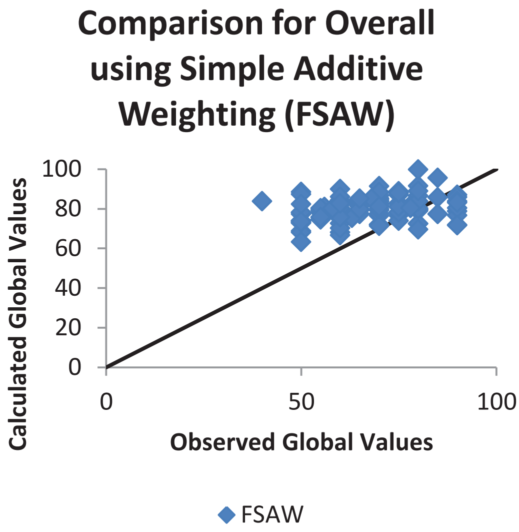

Comparison for Overall using OWA Quantifier (OWAqua)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAqua


Comparison for Overall using OWA Orness (OWAorn)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAorn


Comparison for Overall using OWA Entropy (OWAent)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAent


Comparison for Overall using OWA Optimistic (OWAopt)
Calculated Global Values
Observed Global Values
0
20
40
60
80
100
0
50
100
OWAopt


Comparison for Overall using OWA Pessimistic (OWAper)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
OWAper


Comparison for Overall using Simple Additive Weighting (FSAW)
Calculated Global Values
Observed Global Values
100
80
60
40
20
0
0
50
100
FSAW

F5 Preferences for Choquet Integral

Ecosystem

Ranking for single criterion	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
Most important 4	M-invert	Clear forest	Clear forest	Flora & Fauna	Salinity	Salinity	Flora & Fauna	Clear forest	Clear forest	M-invert
Next 3	Flora & Fauna	M-invert	Flora & Fauna	Salinity	Clear forest	Flora & Fauna	M-invert	Flora & Fauna	M-invert	Clear forest
Next 2	Clear forest	Flora & Fauna	M-invert	Clear forest	Flora & Fauna	M-invert	Salinity	M-invert	Flora & Fauna	Flora & Fauna
Least important 1	Salinity	Salinity	Salinity	M-invert	M-invert	Clear forest	Clear forest	Salinity	Salinity	Salinity
Preference between criteria (h)	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
1st preferred 2nd	Weakly (2)	Strongly (4)	Strongly (4)	Weakly (2)	Weakly (2)	Strongly (4)	Weakly (2)	Not prefer (0)	Not prefer (0)	Strongly (4)
2nd preferred 3rd	Moderate (3)	Moderate (3)	Strongly (4)	Strongly (4)	Moderate (3)	Weakly (2)	Moderate (3)	Weakly (2)	Not prefer (0)	Weakly (2)
3rd preferred 4th	Strongly (4)	Strongly (4)	Strongly (4)	Weakly (2)	Moderate (3)	Moderate (3)	Moderate (3)	Strongly (4)	V.strongly (5)	V.strongly (5)
4th preferred referendum	Not prefer (0)	Weakly (2)	Not prefer (0)	Not prefer (0)	Not prefer (0)	Not prefer (0)	Not prefer (0)	Not prefer (0)	Not prefer (0)	Not prefer (0)
Ranking for pairs of criteria	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
Forest + Flora & Fauna (12)	4th	2nd	1st	4th	6th	5th	3rd	6th	1st	6th
Forest + M-invertebrate (13)	5th	1st	2nd	1st	5th	4th	5th	1st	2nd	1st
Forest + Salinity (14)	3rd	3rd	3rd	5th	1st	3rd	6th	3rd	4th	4th
Flora & Fauna + M-invert (23)	6th	4th	4th	3rd	4th	6th	1st	2nd	3rd	2nd
Flora & Fauna + Salinity (24)	1st	5th	5th	6th	3rd	1st	2nd	4th	5th	5th
M-invertebrate + Salinity (34)	2nd	6th	6th	2nd	2nd	2nd	4th	5th	6th	3rd
Preference between criteria pairs	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
1st preferred 2nd	Moderate (3)	Moderate (3)	Moderate (3)	Moderate (3)	Strongly (4)	Strongly (4)	Weakly (2)	Not prefer (0)	Strongly (4)	Strongly (4)
2nd preferred 3rd	Moderate (3)	Moderate (3)	Weakly (2)	Moderate (3)	Weakly (2)	Weakly (2)	Moderate (3)	Moderate (3)	Moderate (3)	Moderate (3)
3rd preferred 4th	Moderate (3)	Moderate (3)	Weakly (2)	Moderate (3)	Strongly (4)	Moderate (3)	Moderate (3)	Not prefer (0)	Weakly (2)	Moderate (3)
4th preferred 5th	Moderate (3)	Moderate (3)	Weakly (2)	Moderate (3)	Weakly (2)	Weakly (2)	Moderate (3)	Weakly (2)	V.weakly (1)	Weakly (2)
5th preferred 6th	Moderate (3)	Moderate (3)	Strongly (4)	Moderate (3)	Weakly (2)	Weakly (2)	Weakly (2)	Moderate (3)	Not prefer (0)	Moderate (3)
6th preferred referendum	Extremely (6)	Extremely (6)	Extremely (6)	Moderate (3)	Strongly (4)	Extremely (6)	V.strongly (5)	Extremely (6)	V.strongly (5)	V.strongly (5)

Technical

Ranking for single criterion	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
Most important 4	Reliability	Security	Risk	Security	Risk	Security	Risk	Security	Security	Flexibility
Next 3	Flexibility	Flexibility	Security	Reliability	Reliability	Reliability	Security	Reliability	Reliability	Risk
Next 2	Security	Reliability	Reliability	Risk	Security	Risk	Flexibility	Flexibility	Risk	Security
Least important 1	Risk	Risk	Flexibility	Flexibility	Flexibility	Flexibility	Reliability	Risk	Flexibility	Reliability
Preference between criteria (h)	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
1st preferred 2nd	Moderate (3)	V.Strongly (5)	Moderate (3)	Weakly (2)	Moderate (3)	Weakly (2)	Moderate (3)	V.weakly (1)	Strongly (4)	Weakly (2)
2nd preferred 3rd	Moderate (3)	Strongly (4)	Weakly (2)	Strongly (4)	Weakly (2)	Weakly (2)	Strongly (4)	Strongly (4)	Strongly (4)	Extremely (3)
3rd preferred 4th	V.strongly (5)	V.Strongly (5)	Weakly (2)	Weakly (2)	Moderate (3)	Strongly (4)	Moderate (3)	Weakly (2)	Not prefer (0)	Extremely (3)
4th preferred referendum	Extremely (6)	Extremely (6)	Strongly (4)	Extremely (6)	V.weakly (1)	Not prefer (0)	Weakly (2)	Weakly (2)	Not prefer (0)	Weakly (2)
Ranking for pairs of criteria	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
Security + reliability (12)	1st	1st	4th	1st	4th	1st	5th	1st	1st	6th
Security + flexibility (13)	4th	2nd	5th	3rd	5th	4th	4th	2nd	4th	2nd
Security + risk (14)	6th	3rd	1st	2nd	1st	2nd	1st	4th	5th	4th
Reliability + flexibility (23)	2nd	4th	6th	5th	6th	5th	6th	3rd	2nd	3rd
Reliability + risk (24)	3rd	5th	2nd	4th	2nd	3rd	2nd	5th	3rd	5th
Flexibility + risk (34)	5th	6th	3rd	6th	3rd	6th	3rd	6th	6th	1st
Preference between criteria pairs	E1	E2	E3	E4	S6	S7	S8	S20	M1	M2
1st preferred 2nd	Strongly (4)	Strongly (4)	Moderate (3)	Strongly (4)	Weakly (2)	Strongly (4)	Moderate (3)	Moderate (3)	Extremely (6)	Strongly (4)
2nd preferred 3rd	Moderate (3)	Strongly (4)	Weakly (2)	Weakly (2)	Strongly (4)	Weakly (2)	Moderate (3)	V.weakly (1)	Strongly (4)	Moderate (3)
3rd preferred 4th	Moderate (3))	V.strongly (5)	Moderate (3)	Weakly (2)	Weakly (2)	Strongly (4)	Moderate (3)	Weakly (2)	Strongly (4)	Moderate (3)
4th preferred 5th	Moderate (3)	Moderate (3)	Weakly (2)	Weakly (2)	Moderate (3)	Weakly (2)	Moderate (3)	V.weakly (1)	Strongly (4)	Weakly (2)
5th preferred 6th	Weakly (2)	Weakly (2)	Weakly (2)	Strongly (4)	Moderate (3)	Moderate (3)	Strongly (4)	Moderate (3)	Strongly (4)	Weakly (2)
6th preferred referendum	Extremely (6)	Extremely (6)	Extremely (6)	Extremely (6)	Strongly (4)	Strongly (4)	V.strongly (5)	Extremely (6)	Strongly (4)	Extremely (6)

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