# WATER SUPPLY SYSTEM OPTIMISATION – BALANCING OPERATING EFFICIENCY AND WATER SUPPLY SECURITY

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## ABSTRACT

In addressing the impacts on water resources of persistent drought conditions and population increases, there has been considerable capital expenditure for Melbourne, Australia, into new water supply sources and related infrastructure. This investment includes a new desalination plant.

Planning for efficient use of available water resources is one of Melbourne Water's key functions. This planning is complex due to uncertain future hydrological conditions and the mix of available water sources ranging from low cost, low reliability catchments through to higher cost, climate independent desalination. In addition to supply and production considerations, energy costs associated with transfer of water through Melbourne's bulk water supply system also vary depending on time and source used.

With a view to achieving optimal operation of Melbourne's water supply and bulk transfer infrastructure, Melbourne Water and water systems optimisation specialist Optimatics have developed and implemented a decision support system. A multi-objective genetic algorithm optimisation technique is used to identify a range of optimal supply strategies. Key decision makers subsequently choose the strategy that provides the most appropriate balance between short-term annual operating cost and long-term water supply security through the application of multi-criteria decision analysis (MCDA).

## KEYWORDS

**Water resources planning, optimisation, decision support system, multi-criteria decision analysis, water supply security, REALM.**

## 1 INTRODUCTION

Melbourne Water, in collaboration with the other water businesses in Melbourne and its stakeholders, is responsible for carrying out long-term planning and developing a detailed annual system operating plan for the management of Melbourne's water resources. This task is difficult as it involves carefully balancing short-term operating efficiency with long-term water security needs for a complex network of storages and transfer infrastructure, whilst also catering for uncertain future inflow conditions.

The Melbourne Bulk Entitlements Management Committee (BEMC) comprises key customers and stakeholders from the Melbourne water industry, including representatives from government and water retailers, and as such is involved in the decision making process for operation planning.

The decisions made relating to water resources management in Melbourne can involve significant costs in treatment and water transfer, and directly impact Melbourne's water security and the ability to avoid future water restrictions during severe drought. There is a need for a transparent and highly effective decision support system to aid the planning process and to ensure that stakeholders are fully informed as to the options available and the nature of any trade-offs that must be made.

Traditionally, the process has been carried out using a mix of simulation tools and economic modeling, however these tools rely on past experience and an iterative assessment approach, and are becoming insufficient to explore and assess the large number of operating strategies that may exist for a changing infrastructure network.

The decision support system developed and implemented for Melbourne uses a combination of simulation modeling and multi-objective optimisation techniques, with results used to guide a stakeholder selection process based on multi-criteria decision making. This paper presents an overview of this system and discusses an initial trial run performed in Melbourne together with BEMC stakeholders.

# 2 OPERATIONS PLANNING

## 2.1 TRIAL CASE STUDY

The initial test application of the decision support system was led by Melbourne Water in mid 2011 and involved stakeholders from the BEMC participating in a one-day workshop. The system will be explained using examples and results from a trial of the process run as part of the workshop. As the intent of this paper is to present the decision support process, the hypothetical planning scenario used for the trial case study is discussed without including details of the initial outcomes of the process.

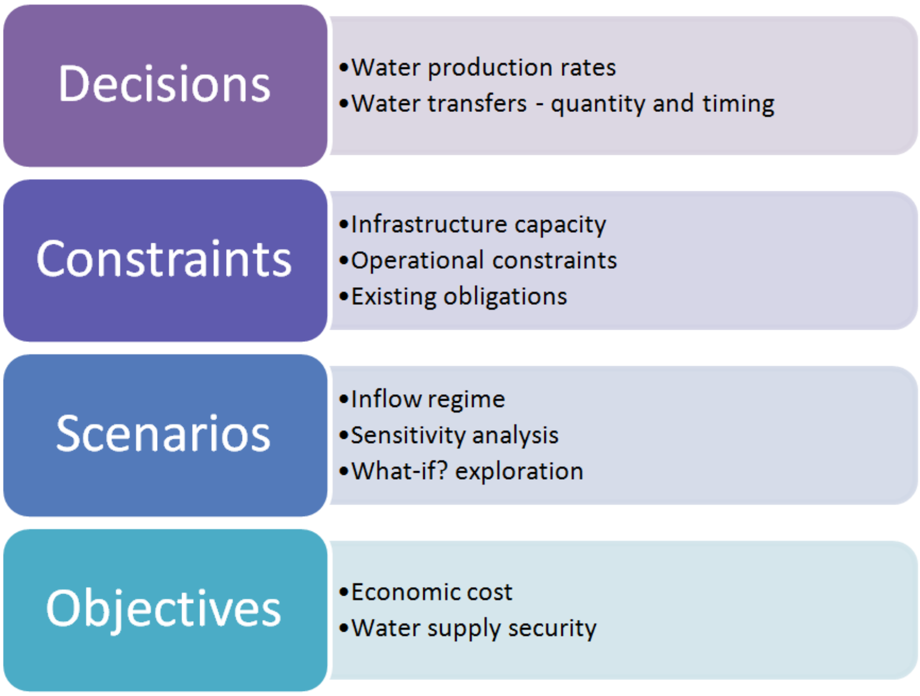
The trial case study was conducted for the Melbourne water supply system, comprising ten large-scale storage reservoirs, over 40 service reservoirs and a transfer system comprising hundreds of kilometers of pipelines, tunnels and aqueducts spanning 160,000 hectares. The trial assumed a future inflow scenario with mild climate change impacts spanning 30 years of annual operating decisions.

## 2.2 PROBLEM DEFINITION

The problem definition as summarised in Figure 1 specifies the decisions, constraints and objectives that drive the optimisation component of the decision support system. It also specifies the types of scenarios that might be considered (e.g. future climate conditions). The key decisions include the optimal volumes to be taken from higher cost sources, the optimal distribution of this water within the system and the timing of these volumes so as to achieve a balance between the objectives that include cost and water supply security.

Defining the optimisation problem in detail and specifying the measures by which an operating strategy is judged, is an important first step in beginning the decision making process, and is crucial to providing an effective outcome from the planning process. This step is often skipped when using a simulation only approach, whereby an operation strategy is determined based on hydrological and hydraulic simulation first, with costs, environmental impacts and social outcomes calculated second. One of the benefits of using an optimisation approach is that these factors are all considered together.

*Figure 1: Optimisation problem definition*



## 2.3 PROBLEM COMPLEXITY

The 30-year operations optimisation problem described above involves well over 4000 decisions when considering the full set of water production and transfer rates as shown in Table 1 below. The optimisation problem used for the initial trial benefited from grouping a number of these decisions, but even with these simplifications the search space was of the order of $10^{476}$. For reference, the number of atoms in the universe is estimated to be $10^{80}$.

Trial-and-error simulation is clearly an ineffective means of searching for a near-optimal operation strategy when dealing with a search space of this size. Instead an automated optimisation approach is adopted that is capable of assessing tens of thousands of candidate operation strategies and rapidly converging to a set of near-optimal solutions.

*Table 1: 30-year operations optimisation problem*

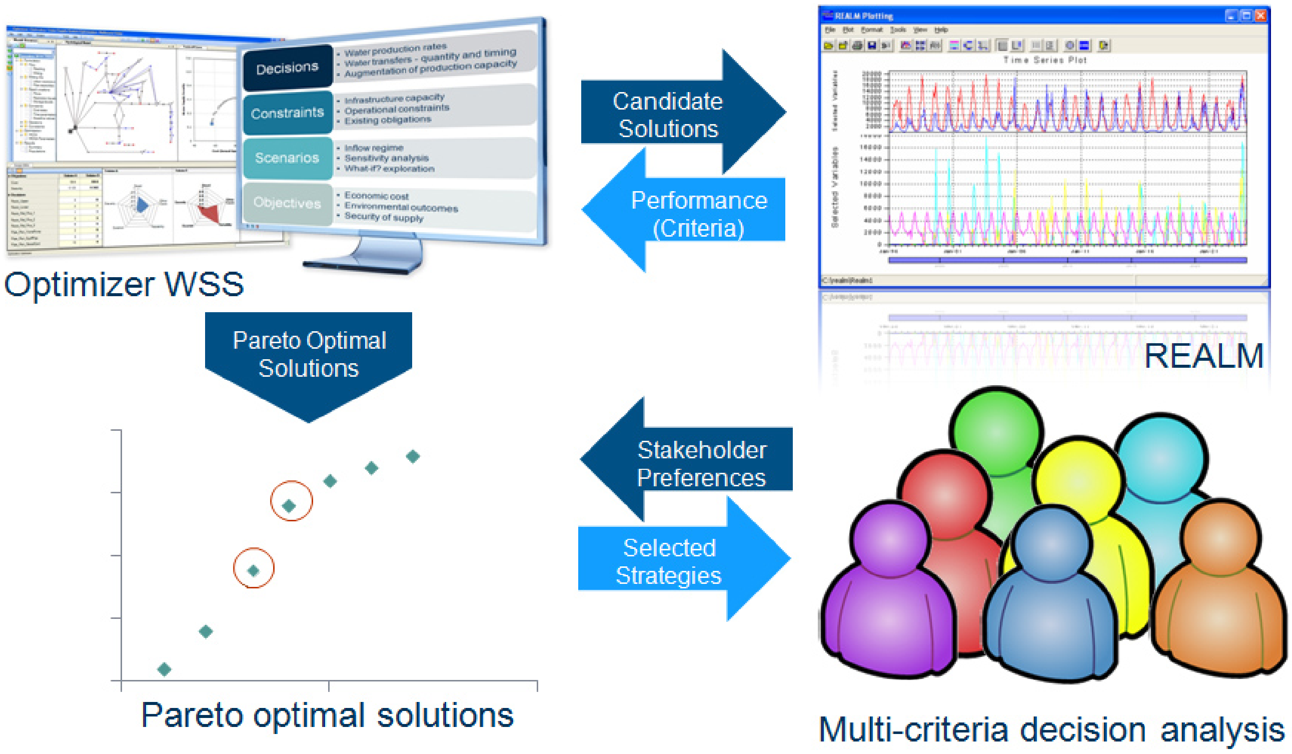
| **Operating Decision** | **Decisions** | **Options** |
|---|---|---|
| Annual desal order | 30 | 5 |
| Sugarloaf transfers | 360 | 5 |
| Yarra pumping rate | 360 | 5 |
| Tarago output rate | 360 | 5 |
| Transfers | 3000+ | 5 |

Total possible combinations:
$5^{30} * 5^{360} * 5^{360} * 5^{360} * 5^{3000} = 5^{4110}$

# 3 SYSTEM OVERVIEW AND METHODOLOGY

The decision support system developed for this project, named Optimizer WSS (Water Supply Systems), is comprised of a multi-objective optimisation engine coupled with a headworks simulation model (REALM), and is used to identify a range of near-optimal operation strategies (Pareto optimal solutions) which are then ranked via a stakeholder selection process to identify one or more recommended operating strategies. A conceptual flowchart of the decision support system process is shown in Figure 2, and the various components are explained below.

*Figure 2: Decision support system process overview*



## 3.1 SIMULATION MODEL

The decision support system uses the Resource Allocation Model REALM (Perera et al., 2005) configured to Melbourne's water supply system. This water resource model is used for modeling water supply system behavior, and can be used, among other purposes, to assess a proposed operating strategy against a range of future potential hydrological scenarios. Typically an optimisation run will require at least 10,000 REALM simulations in order to converge on a set of near-optimal solutions. For each simulation a candidate solution is created by Optimizer WSS comprising options chosen for monthly production and transfer rate decisions, and REALM is used to simulate this operation strategy and provide outputs that indicate the degree to which the optimisation objectives (relating to cost and water security) have been achieved. Optimizer WSS learns from the outputs which strategies perform well and which strategies perform poorly as it searches for the best solutions to the optimisation problem.

As future inflow conditions are uncertain, REALM can also be configured to test each operation strategy against multiple inflow conditions. As the optimisation approach requires upwards of 10,000 strategies to be assessed, the number of inflow replicates considered for each assessment must be kept to a small number so as to keep the optimisation run time down. Optimatics uses distributed computing clusters both in its Adelaide office and through accessing cloud computing resources to enable parallel processing of scenario evaluations and reduce optimisation run times to only a fraction of the time that would be required if only a single desktop PC was used.

## 3.2 MULTI-OBJECTIVE OPTIMISATION

A unique and innovative feature of the decision support system is the use of multi-objective optimisation. In optimising the supply and transfer of water resources, there is an important trade-off between financial efficiency and water supply security. For this reason a multi-objective genetic algorithm optimisation technique, NSGA-II (Deb et al., 2002), was used. This technique is useful in identifying a range of Pareto optimal supply strategies, as shown in Figure 3. This Pareto optimal front represents the trade-off between the two objectives of interest. 30-year operation strategies simulated using REALM can be plotted in terms of annual operating cost and a water supply security metric (calculated, for the purposes of initial testing, based on number of months where restrictions are avoided, duration of restrictions and severity of restrictions). For all solutions represented by grey circles that sit on the Pareto front, there exist no other strategies whereby water supply security can be improved without resulting in increased cost.

As each strategy has been simulated using REALM as part of the optimisation process, detailed simulation results can also be scrutinized if required, or further assessed in terms of metrics of interest as shown in Figure 4. These charts have been constructed to allow comparison between results, with metrics of interest scaled to a number between one (excellent) and zero (poor). An ideal scenario is thus one that is completely filled with colour.

A common criticism of the use of single-objective optimisation approaches for planning is that the relative importance of key objectives must be defined prior to performing the optimisation. This is often not an issue when all objectives can readily be expressed in dollar terms, however this can lead to less than ideal outcomes when dealing with objectives with potential environmental, social or political impacts. For example, in viewing the Pareto front in Figure 3, stakeholders are able to make an informed decision as to which of the myriad of available Pareto optimal strategies to choose. Although all strategies displayed here can be considered optimal for a particular relative weighting of objectives, inspection of the shape of the front tells us much about the nature of the problem we are dealing with.

For example, in comparing the annual operating cost of strategies labeled B and C, the decision-maker might consider recommending an increase in operating budget of approximately 25% to improve the water security measure by approximately 50%, however a further increase in budget to move beyond point C to D on the front would not be justified as it would result in very little additional benefit. In a similar way a decision between choosing strategy D and the slightly more expensive strategy E is relatively straightforward. There is a very strong case to justify a small increase in budget at this point to achieve nearly twice the water supply security.

This clarity is lost when objectives are weighted and lumped into a single objective function, and the decision maker has little control as to which point on this front emerges from the optimisation as the single recommended strategy. Without using multi-objective optimisation, often the only remedy is to perform multiple optimisation runs to test the sensitivity of the weights chosen.

*Figure 3: Example trade-off curve for optimisation objectives. Components of these objectives (reliability, duration, severity, desalination costs, other costs) are shown for five Pareto optimal solutions. Actual cost values withheld.*

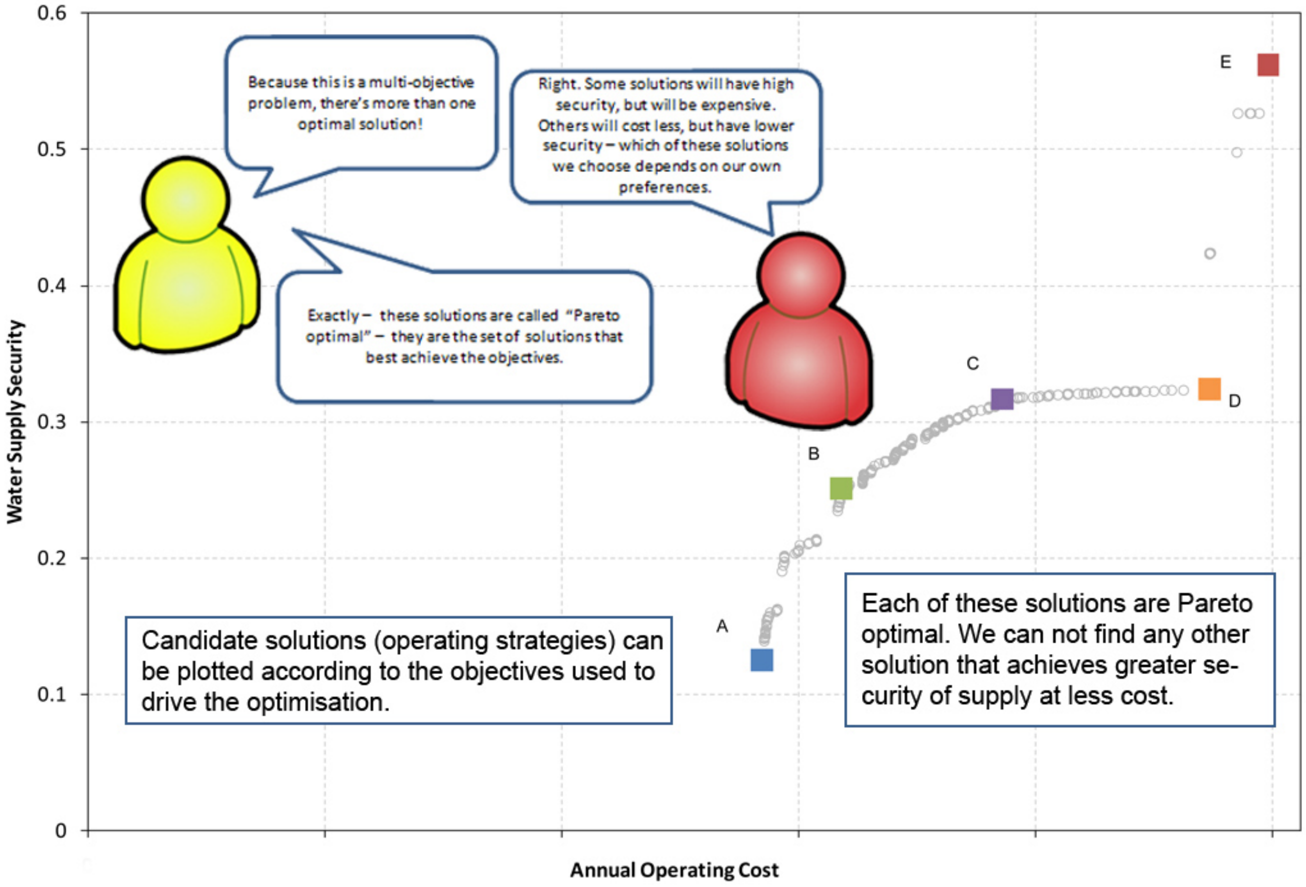
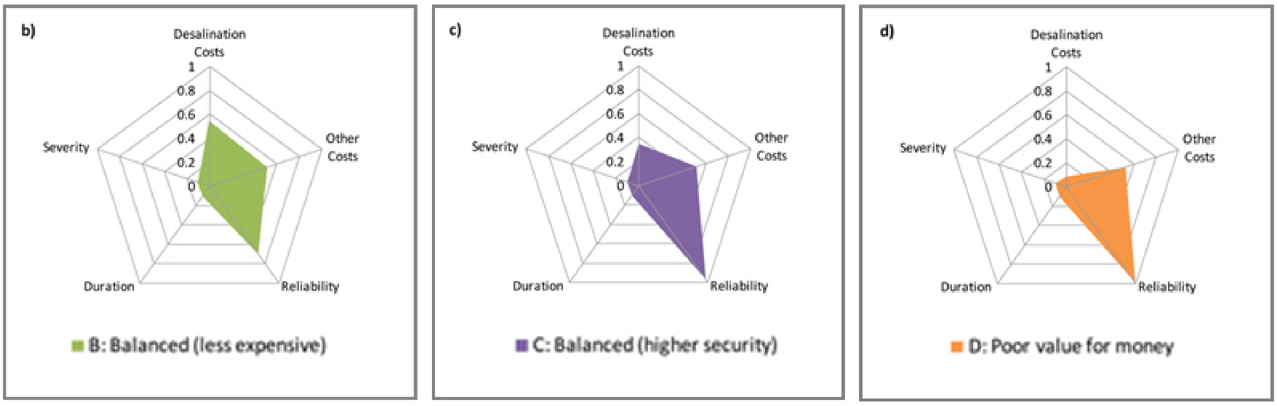


*Figure 4: Example solutions displayed in terms of criteria of interest*



## 3.3 SELECTION PROCESS

Whilst two objectives are used to drive the optimisation, the outputs can be further broken down into a number of long-term and short-term criteria that may be of interest to stakeholders in assessing the candidate strategies, with some examples of these used for initial tests listed in Table 2.

In presenting candidate strategies to decision makers, a multi-criteria decision analysis (MCDA) approach is used to consider the relative merits of each strategy leading to an informed decision as to the overall preferred operating plan. The MCDA process requires each stakeholder to state their relative preference for each criteria, and the preferences from all stakeholders are used to rank each of the Pareto optimal strategies, such that one or more preferred strategies can be nominated for further scrutiny and implementation.

Prior to the one-day workshop held with BEMC stakeholders in June 2011, Optimizer WSS was used to perform an optimisation run for the hypothetical planning scenario described above, with hundreds of distinct Pareto optimal solutions generated. At the workshop, BEMC representatives were grouped by member organization and invited to complete an exercise that identified their relative preference between each pair of criteria, resulting in a weight being attributed to each criterion of interest. Hypothetical examples of the weights are shown in Figure 5, but these do not correspond to the preferences identified at the workshop. Individual results for the hypothetical stakeholder with the highest preference for minimizing cost, and the hypothetical stakeholder with the highest preference for maximizing security of supply are shown as examples, together with the combined results across the two hypothetical stakeholders.

These weights based on relative preferences were then used to rank the Pareto optimal strategies that resulted from the optimisation run in order to identify the region on the Pareto front that was of most interest to the group, and subsequently recommend a small number of strategies for further scrutiny.

*Table 2: Long-term and short-term criteria considered in trial selection process*

Long-term Criteria

**Minimise Cost:** The future cost of operations and system augmentations discounted to the present year. This includes desalinated water, treatment, energy purchases and sales, future augmentations, and revenue lost as a result of restrictions.

**Maximise Water for the environment:** Occurrence of higher than required environmental flow releases from the system. This sums up the number of months of higher than required flows in three water supply catchments; Yarra, Thomson and Tarago.

**Maximise security of supply:** This is indicated as the loss of consumer willingness to pay, resulting from water restrictions. High security of supply is indicated by a low loss of willingness to pay. This criterion summarises the impacts to the community of restrictions.

**Maximise storage levels during droughts**: The minimum total system storage volume modelled over the 30-year period.

Short-term Criteria

**(5-Yr) Minimise Cost:** The cost of operations and system augmentations over the next 5 years, discounted to the present year.

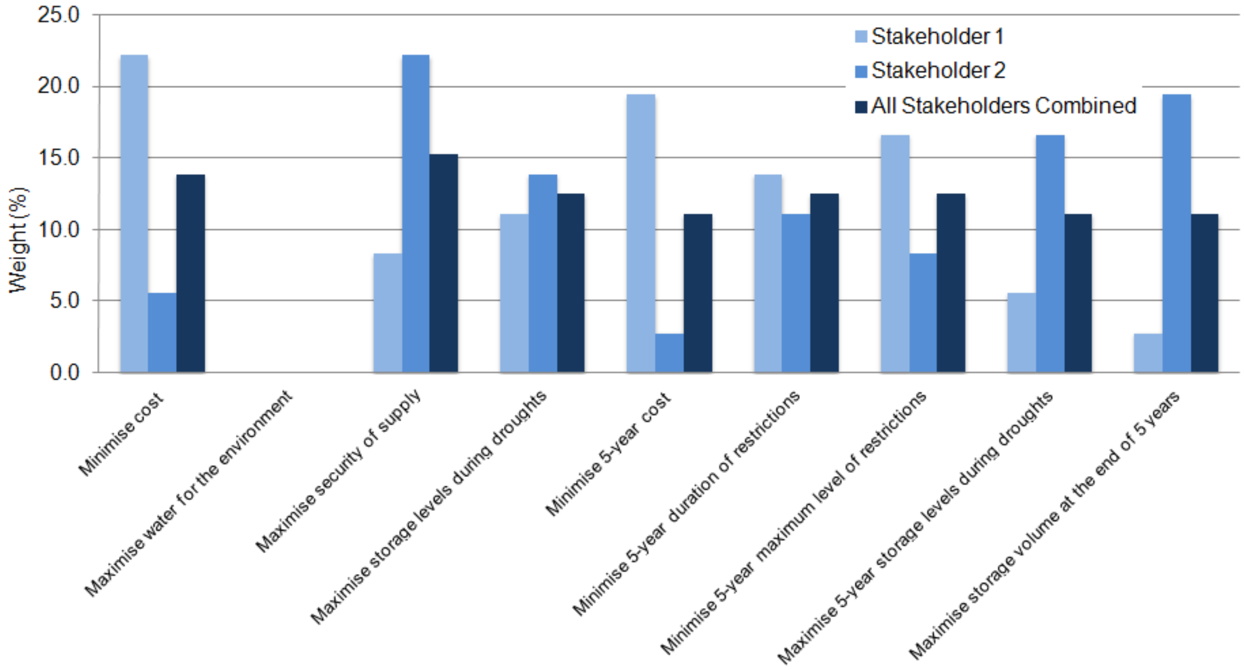
**(5-Yr) Minimise duration of restrictions**: The longest duration of restriction events over the next five years

**(5-Yr) Minimise level of restrictions:** The highest level of restrictions during the next five years, as defined by the Drought Response Plan

**(5-Yr) Maximise storage levels during droughts**: The minimum total system storage volume modelled over the next five years

**(5-Yr) Maximise End Storage Volume**: The total system storage volume at the end of the next five years.

*Figure 5: Relative preferences for each criterion for trial scenario for two hypothetical stakeholders and combined results across the two stakeholders*



# 4 CONCLUSIONS

Whilst a trial application is described in this paper by way of example, the decision support system is currently being used by Melbourne Water to facilitate decision-making with the BEMC to assist preparing its annual operating plan.

Stakeholders involved in the initial trial and ongoing use of the decision support system are supported by a decision-making framework that removes subjectivity, provides justification for decisions, and enables improved communication of planning outcomes. As the optimisation framework requires the decisions, constraints and success measures to be clearly defined, stakeholders can be presented with the assumptions and options being considered in the planning process, and where appropriate provide input either through formulation of the optimisation problem, proposing a range of "what-if" scenarios for investigation, or through input into the multi-criteria analysis process. This level of transparency and stakeholder engagement improves on traditional approaches based on simulation only.

The use of the system to identify efficient operating strategies can be of assistance to Melbourne Water in achieving its 2018 targets of zero greenhouse emissions and 100% renewable energy use. In addition to ongoing operations planning, the decision support system is also effective in helping Melbourne Water to assess the potential benefits of future infrastructure augmentations to the network.

## ACKNOWLEDGEMENTS

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