Multi-Objective Optimisation of Water Resources Systems: A Shared Vision

by

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Abstract

Water resources systems are operated for many uses such as for municipal water supply, irrigation, hydro-electric power generation, flood mitigation, storm drainage, and for recreation. Water resources systems may also serve as places of cultural and spiritual significance. Decision-making in this context is inherently multicriterial, often requiring multi-disciplinary participation with a view to seeking an optimal solution or, at best, a compromise between conflicting interests for water. Water resources planning involves a thorough understanding of not only the quantitative aspects such as the volumes of water harvested and released from reservoirs but also of the qualitative factors that underpin the shared vision for the operation of water resources systems for the benefit of all stakeholders.

The aim of this study was to develop a structured multi-objective optimisation procedure for the optimisation of operation of water resources systems considering climate change. For this purpose, the integration of quantitative and qualitative information of water resources systems was achieved using a combined multi-objective optimisation and sustainability assessment approach as part of a three-phase procedure. This procedure was tested through the preparation of optimal operating plans for a case study of the Wimmera-Glenelg Water Supply System (WGWSS), assuming a range of hydro-climatic conditions. The WGWSS is located in north-western Victoria in Australia and is a multi-purpose, multi-reservoir system which is operated as a single water resources system; with many possible combinations of operating rules.

Phase (1) of the procedure involved the formulation of a higher order multi-objective optimisation problem (MOOP) for the WGWSS. A higher order MOOP is defined in this study as a problem that is formulated with more than three objective functions. The 18 objective functions of the MOOP were developed from four major interests for water identified in the WGWSS viz. environmental, social, consumptive, and system-wide interests. The 24 decision variables of the MOOP represented the complex operating rules which control the movement of water within the headworks. The constraints of the MOOP, in terms of the physical characteristics of the WGWSS, were configured in a simulation model. The formulation of the higher order MOOP demonstrated that the

procedure provided a means to explicitly account for all the major interests for water and to incorporate complex operating rules.

Phase (2) of the procedure involved the development of an optimisation-simulation (O-S) model for the purposes of solving the higher order MOOP formulated in Phase (1). The optimisation engine was used to perform the search for candidate optimal operating plans and the simulation engine was used to emulate the behaviour of the system under the influence of these candidate optimal operating plans. The setup of the optimisation engine was based on a widely used evolutionary algorithm and the setup of the simulation engine involved the replacement of an available simulation model with a surrogate model that had greater flexibility and stability in terms of changing from one operating plan to another. Three hydro-climatic data sets were used to represent historic conditions and future climate conditions assuming a range of greenhouse gas emissions. The setup of the optimisation engine was described in terms of the genetic operators (i.e. selection, crossover, and mutation) and the optimisation parameters (i.e. genetic operator settings, population size etc).

Phase (3) of the procedure involved the development of an analytical approach which used the Sustainability Index (SI) to evaluate optimal operating plans. The SI was used to aggregate the 18 objectives of the higher order MOOP, either separately in terms of the major interests for water, or collectively in terms of the sustainability of the WGWSS. The SI was shown to have the flexibility to include a range of interests for water together with scaling characteristics that did not obscure poor performance. The SI provided a simple means to rank optimal operating plans along the Pareto front with respect to all 18 objectives. The Pareto front is the set of optimal trade-offs between the conflicting objectives. Moreover, the SI was extended to incorporate stakeholders' preferences for the purposes of selecting preferred Pareto-optimal operating plan(s) under the three hydro-climatic conditions mentioned earlier in Phase (2). The resulting Weighted Sustainability Index (SI^j) for the j^{th} stakeholder had all the benefits of the SI in terms of flexibility and scalability as described earlier.

Importantly, the key innovation of this procedure is that it combines the formation of Pareto fronts for a range of hydro-climatic conditions with sustainability principles to deliver a practical tool that can be used to evaluate and select preferred Pareto-optimal solutions of higher order MOOPs for any water resources system.

Declaration

"I, Walter Rafael Godoy, declare that the PhD thesis entitled 'Multi-Objective Optimisation of Water Resources Systems: A Shared Vision' is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work."

Signature: [redacted] Date: 20 September 2015

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Chapter 1. Introduction

1.1 Background

Water resources systems are operated for many uses such as for municipal water supply, irrigation, hydro-electric power generation, flood mitigation, and storm drainage (Linsley et al., 1992). These systems also play an important social role in providing recreational amenity and a place of cultural and spiritual significance (GWMWater 2012a; 2012b). This means that decision-making in this context is inherently multicriterial, often requiring multi-disciplinary participation with a view to seeking a compromise or consensus between conflicting interests for water (Belton and Stewart, 2002). Water resources planning involves a thorough understanding of not only the quantitative aspects such as the volumes of water harvested and released from reservoirs but also of the qualitative factors that underpin the shared vision for the operation of water supply systems for the benefit of all stakeholders (Loucks and Gladwell, 1999; Deb, 2001).

The Wimmera-Glenelg Water Supply System (WGWSS) is located in north-western Victoria in Australia, and is a multi-purpose, multi-reservoir system which harvests water from two major river systems viz. the Wimmera River and the Glenelg River. The system is managed through a complex regime of operating rules to meet a range of interests for water including environmental, social, and consumptive user interests. The 12 headworks storages have their own unique hydrologic, environmental and socio-economic attributes and are operated as a single water resources system; with many possible combinations of operating rules (Godoy et al., 2009). In recent times the system has undergone significant transformation from an open-channel system to a pressurised pipeline system, with most of the associated water savings re-allocated to the environment. This has fundamentally changed the operating rules from a harvest-then-release regime, to one that passes a larger proportion of the system inflow for environmental purposes. Moreover, the recent drought period caused a 78% reduction of the average annual inflow to the system over the period July 1997 to June 2010 compared to the average annual inflow over the period July 1891 to June 1997. This has added a new dimension to the operation of the WGWSS requiring innovative planning to ensure uncertainties in future climate do not diminish stakeholders' rights to water.

Water resources planning studies are usually supported by simulation and optimisation models which allow examination of the potential impacts of changes to hydrological conditions, infrastructure and operating rules without incurring the costs and risk that would be incurred if such changes were to happen to in practice (Palmer et al., 1999). Simulation models attempt to represent all the major characteristics of a system and are tailored to examine "what if?" scenarios (Palmer et al., 1999). Simulation modelling is widely used in Australia and internationally to evaluate the performance of regulated river basins (Perera et al., 2005; Kuczera et al., 2009). Optimisation models are characterised by a numeric search technique and are better suited to address "what should be?" questions. Of particular relevance to this thesis, is the use of combined optimisation–simulation (O-S) models given that optimisation methods can be directly linked with trusted simulation models (Labadie, 2004).

Many of the interests for water that exist in water resources systems are conflicting and non-commensurable which can be generally reduced to multi-objective optimisation problems (MOOPs) in which all objectives are considered important. MOOPs consist of a number of objectives subject to a number of inequality and equality constraints as described by Srinivas and Deb (1995):

$$\begin{aligned} &\text{Minimise/Maximise} \quad && f_i(x) && i = 1,2,\ldots, I \\ &\text{Subject to} && g_j(x) \le 0 && j = 1,2,\ldots, J \\ & && h_k(x) = 0 && k = 1,2,\ldots, K \end{aligned} \qquad (1.1)$$

The parameter x is a p dimensional vector having p design or decision variables. The aim is to find a vector x that satisfies J inequality constraints, K equality constraints and minimises/maximises I objective functions. Of particular relevance to this thesis, are those problems where three or more objectives are optimised simultaneously; the so called *many-objective* (or *higher order*) MOOPs. Solutions to MOOPs are mathematically expressed in terms of superior or *non-dominated* solutions. This highlights the difficulty with MOOPs in that there is usually no single optimal solution with respect to all objectives, as improving performance for one objective means that the quality of another objective will decrease. Instead there is a set of optimal trade-offs between the conflicting objectives known as the *Pareto-optimal* solutions or the *Pareto front* (Deb, 2001). Deb (2001) describes the ideal multi-objective optimisation procedure as one that involves bringing together quantitative and qualitative information as follows:

> " *Step 1: Find multiple trade-off optimal solutions with a wide range of values for objectives.*
>
> *Step 2: Choose one of the obtained solutions using higher-level information*." (Deb, 2001, p4)

Present day water planning processes around the world highlight a desire to move towards sustainable water resources systems that have a common view or shared vision for the operation of the system (Loucks and Gladwell 1999). For this to occur the MOOP needs to be formulated in such a way that it guides the search towards optimal solutions that strive to improve the sustainability of the water resources system. Loucks and Gladwell (1999) argued that sustainable development can only succeed with sustainable water resources systems supporting that development. In their review of the many definitions of *sustainable development*, they propose the following definition for the management of water resources systems:

> "*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*." (Loucks and Gladwell, 1999, p30)

As water resources planning is for the future, forecasts of future conditions are essential (Linsley et al., 1992). This is especially true in planning studies that have a long-term planning period often 50 to 100 years into the future. Fortunately, the availability of general circulation models (GCMs) make it possible for planning processes to incorporate the latest advances in the projection of future climate and to understand which operating rules are paramount in an uncertain climate future. In terms of forecasts of future conditions, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated that:

> "....*the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*." (IPCC, 2007, p2)

1.2 Aims of the study

The aim of this project is to develop a structured procedure for the optimisation of operation of water resources systems considering climate change. This procedure will take explicit account of:

- competing objectives concerning all major interests for water;
- complex operating rules that regulate the movement of water through the headworks system; and
- a range of hydro-climatic conditions.

This procedure will be based on the ideal multi-objective optimisation approach which firstly strives to find Pareto-optimal solutions with a wide range of values for each objective function, followed by the selection of preferred optimal solution(s) based on stakeholders' preferences. The procedure will be developed and tested using the WGWSS case study. The remainder of this section provides further details of the three areas of study highlighted above.

Developing a thorough understanding of the major interests for water in water resources systems provides valuable insights into the type and extent of conflict that may exist between the different uses for water. In the WGWSS for example, many of the 12 headworks storages having conflicting interests in terms of passing water for provision of environmental flows; holding sufficient water in store for consumptive needs; and holding a minimum volume in store for provision of recreation amenity. In this example, the extent of conflict between passing water for environmental purposes versus holding water in store for consumptive and recreation needs would probably have a greater level of conflict than that between holding water in store for consumptive needs versus holding water in store for recreation needs. This process of identifying the major interests for water forms the basis of the conflicting objectives to the optimisation problem.

Management of the natural forces of precipitation, evaporation, and streamflow requires the collection, drainage, and transfer of water with consideration to varying scales both spatially and temporarily; particularly in multi-reservoir systems such as the WGWSS. Reservoir operation is a complex and challenging task, not only because of the presence of multiple conflicting objectives but also owing to seasonal and stochastic variations in the demand for and supply of water. Operating rules for reservoir management include flow rates and upper limits of harvest/release and storage target volumes throughout the year for a range of objectives as established through the identification of the major interests for water described above. The availability of trusted simulation models serve as useful tools for the purposes of testing any changes to the current operating rules without incurring the costs and risks of implementing such changes in practice.

Moreover, the inclusion of a range of hydro-climatic conditions within the structured procedure provides a two-fold benefit. One benefit is that it allows the search for candidate optimal operating plans to be undertaken under the various hydro-climatic conditions. This means that the formation of Pareto fronts can be established for a range of hydro-climatic conditions. Another benefit of the inclusion of a range of hydro-climatic conditions is that it also allows for comparisons of the same candidate optimal operating plan to be made under the various hydro-climatic conditions. Both these benefits allow for a thorough testing of the robustness of optimal operating plans as part of the selection of preferred optimal solution(s) based on stakeholders' preferences. Moreover, the use of high quality climate projections into the future (together with the inclusion of the major interests for water) are consistent with the concept of sustainable development presented in Section 1.1.

1.3 Research methodology

Following a critical review of multi-objective optimisation modelling in water resources planning, the concept of the proposed multi-objective optimisation procedure was developed on the ideal multi-objective optimisation procedure (Deb, 2001) which integrates quantitative and qualitative information. Firstly, an O-S model is used to provide the quantitative information in terms of the Pareto-optimal solutions, followed by the selection of a preferred optimal operating plan using qualitative information in terms of stakeholder preferences. The proposed multi-objective optimisation procedure comprises three phases as follows:

Phase (1) Formulation of MOOP;
Phase (2) Development of O-S model; and
Phase (3) Selection of preferred Pareto-optimal solution(s).

Note that while Sections 1.3.1 to 1.3.3 describe the three phases with reference to the WGWSS case study, the proposed procedure for optimisation of operation of complex water resources systems can be applied to any water resources system.

1.3.1 Phase (1) - Formulation of MOOP

1.3.1.1 Identification of major interests for water

Much of the information required to identify the major interests for water in the WGWSS had already been collected as part of various recently completed planning studies. A desktop study of this information was undertaken as part of this thesis together with a description of the relevant parts of the simulation model which formed part of the O-S model (as explained later in Section 1.3.2). Four broad categories of interests for water were identified viz. environmental, social (i.e. in terms of recreation, water quality, and cultural heritage), consumptive, and those that affected all users system-wide. As part of this identification process, any relevant criteria by which to evaluate candidate optimal operating plans was also identified together with the various interests for water. For these criteria to be incorporated in the higher order MOOP, a suitable unit of measure was developed to evaluate candidate optimal operating plans on a quantitative basis with respect to the interests for water identified. Moreover these performance metrics were aimed at providing the basis for meaningful dialogue amongst the stakeholders and the decision maker (DM) in terms of the sustainability of the interests for water identified.

1.3.1.2 Specification of objective functions, decision variables, and constraints

As with any MOOP, its formulation required the specification of objective functions, decision variables, and constraints. The specification of the objective functions was developed on the key assumption that the sustainability of the WGWSS was an overall goal. This starting point led to the concept of a problem hierarchy where by each sub-criteria level represented the sustainability of the system from a different vantage point or perspective. For this thesis, the second level of the problem hierarchy represented the four broad interests for water described in Section 1.3.1. This second level was used to provide a means to describe the sustainability of the four individual interests for water (of which collectively described the sustainability of the WGWSS from the perspective of all interests for water). The lowest level criteria was used to represent the objective functions for the MOOP. These lowest level criteria represented the underlying conflicts of the problem and were directly linked to the interests for water described in Section 1.3.1. The decision variables for the higher order MOOP were expressed in terms of water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. The constraints of the problem were specified both in terms of the formulation of the MOOP and also in terms of the real-world limitations of the WGWSS.

1.3.2 Phase (2) - Development of O-S model

1.3.2.1 Setup of optimisation engine

The setup of the optimisation engine was aimed at demonstrating the novelty of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*. To that end, the O-S model includes the widely accepted evolutionary algorithm known as the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) developed by Deb et al. (2002). Further details regarding NSGA-II are provided in Section 2.2.4. The purpose of the optimisation engine was to find the best non-dominated operating plans for evaluation using the sustainability index described in Section 1.3.3.1. The term *generation* refers to a (single) iteration of the O-S model. This setup was described in terms of the operators of the genetic algorithm (GA) and the optimisation parameters. The genetic operators (i.e. selection, crossover, and mutation) were used to perturb the population of candidate optimal solutions in order to create new and possibly better performing solutions compared to those in previous generations. The optimisation parameters (i.e. parameter representation, probability of selection, probability of crossover, probability of mutation, stopping criteria, and population size) were used to control the search capabilities of the GA.

1.3.2.2 Setup of simulation engine

The setup of the simulation engine was aimed at performing as many simulation runs as was required to find the best non-dominated operating plans and to provide the basis for a far reaching or *global* search for candidate optimal solutions. For this purpose, a surrogate model was developed to provide the flexibility and stability required to change from one operating plan to another (as required by the optimisation engine). The REsource ALlocation Model (REALM) software package (Perera et al., 2005) was used to simulate the harvesting and bulk distribution of water resources within the WGWSS. Further details regarding REALM are provided in Section 2.2.4. The derivation of the simulation data inputs representing the hydro-climatic data and water demand data of the WGWSS was also described. The historic hydro-climatic data extended from January 1891 to June 2009. The latest advances in the projection of future climate were used to represent "low to medium level" and "medium to high level" greenhouse gas (GHG) emissions. These two plausible GHG emission scenarios extended from January 2000 to December 2099.

1.3.3 Phase (3) - Selection of preferred Pareto-optimal solution(s)

1.3.3.1 Design of an analytical approach to evaluate candidate optimal operating plans

An analytical procedure was developed for the purposes of evaluating Pareto-optimal operating plans. The evaluation of Pareto-optimal operating plans in this context refers to the ranking of plans in terms of the sustainability of WGWSS; with respect to all objectives. For this purpose, a well-established sustainability index developed and refined by Loucks (1997), Loucks and Gladwell (1999), and Sandoval-Solis et al. (2011) was used to aggregate all the objectives of the higher order MOOP. One of the key attractions to this Sustainability Index (SI) was that it could be used to summarise the performance of alternative policies from the perspective of different water users. In the context of this thesis, this attribute was particularly beneficial as it was used to explicitly account for all the major interests for water in the WGWSS.

1.3.3.2 Evaluation of optimal operating plans under a range of hydro-climatic conditions

The evaluation of optimal operating plans involved applying the analytical approach described in Section 1.3.3 to the outputs of the O-S modelling runs. In the first instance, this evaluation process was undertaken on the optimal operating plans found by the O-S model assuming historic hydro-climatic conditions. This allowed a direct comparison of the O-S modelling results with the base case operating plan and to explain the implications of new optimal operating plans against a known reference point to the DM. In order to incorporate a range of hydro-climatic conditions, the low to medium level and medium to high level GHG emissions described in Section 1.3.2.2 were fed to the simulation engine. This allowed for the direct search of optimal operating plans under two plausible future GHG emission scenarios and for a comparison with those found under historic hydro-climatic conditions.

1.3.4 Concluding remarks on methodology

The research methodology that is described in Sections 1.3.1 to 1.3.3 was influenced by a number of important factors which are directly related to solving higher order MOOPs, viz; (i) the slow convergence of solutions to the Pareto front; and (ii) the high computational costs required to progress this search, particularly in the absence of parallel computing. Research has shown that the proportion of non-dominated solutions to the population size becomes very large as the number of objectives increases (Fleming et al., 2005; Deb, 2011).

With respect to a population-based optimisation search, this increase in objectives has the effect of slowing the progression (i.e. *convergence*) of the population of solutions to the Pareto front. This slow convergence is largely attributed to a procedure (referred to in this thesis as the “dominance test”) which is applied to the solutions of the population in order to determine their non-dominance classification with respect to other solutions of the population. For example, in the case of two very similar candidate optimal solutions whose values of all but one of the many objectives are equal, the solution which has the better performing objective will dominate the other, even if that performance is minuscule. With little thought, it is easy to accept that the creation of new candidate optimal solutions will be based on solutions that are a very similar, resulting in slow progression towards the Pareto front.

This slow convergence means that a greater number of O-S modelling generations are required to progress the solutions towards the Pareto front. An increase in the number of generations requires greater computational processing effort, which in the case of population-based optimisation searches can be addressed through distributed or shared memory parallel computing architectures. However, such parallel computing capabilities were not available for this study, which meant that simulation runs for all solutions of the population had to be completed in series (i.e. one run at a time) before the optimisation search could be executed.

For these reasons (of slow convergence and high computational costs), the number of generations performed by the O-S model was limited to five in number (throughout this thesis). Importantly, this is not to be confused as a research limitation given that the novelty of this study is that of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*.

1.4 Significance of the research

A recent review of water entitlement arrangements in the WGWSS exemplifies the significance of the research presented in thesis from a number of perspectives. The aims of the Bulk and Environmental Entitlements Operations Review ("the review project") were developed as part of a series of government planning studies in Victoria (2000 to 2011) which were tasked with re-allocating water savings from the transformation of the open-channel delivery system to a pressurised pipeline system (GWMWater, 2014). The overall aim of the review project was to investigate new and potentially better operating rules for the headworks system. The scope of the review project was based on 11 storage management objectives which were generally consistent with the sustainability principles described earlier (GWMWater, 2014). These storage management objectives were developed in order to ensure that the system was operated to protect users' rights to water.

The review project was supported by the outputs of a simulation model which has had over 20 years of development in numerous simulation modelling studies largely for the purposes of providing system performance variables over long term planning periods (Godoy Consulting, 2014). In recent times, this high quality simulation model was endorsed by the Murray-Darling Basin Authority as part of its model accreditation process under the Murray-Darling Basin Plan (MDBA, 2011). It is worth highlighting that researchers generally agree that the use of trusted simulation models would have the potential of giving stakeholders and DMs greater confidence in O-S modelling results (Maier et al., 2014). The major stakeholders involved in the review project included the water entitlement holders, the relevant catchment management authorities, and the Department of Environment, Land, Water & Planning. Public submissions were also sought on the draft report to guide the decision-making process for the decision maker (DM), being the responsible Minister administering the *Water Act 1989* (Vic).

The outputs of the study showed that current practice in the WGWSS as demonstrated by the modelled operating rules (collectively referred to as the "base case operating plan") was generally consistent with stakeholders' storage management objectives (GWMWater, 2014). Of the 38 recommendations that were made to improve system operation, the social interests for water in terms of recreation amenity was one area that received the greatest level of attention (i.e. this area deals with 10 out of 38 recommendations). GWMWater (2014) adds that the majority of the public submissions focused on the social interests for water in terms of preserving and/or restoring recreation amenity. So much so that the recommendation to the DM is for there to be a range of works employed to address this area of interest including increasing the recreation water entitlement. Another area which received a great deal of attention based on the number of recommendations (i.e. 8 out of 38 recommendations) was the need to develop more holistic and collaborative management plans for improving environmental watering arrangements between water agencies.

Hence, the review project highlights the following key attributes which can be structured for many such complex water resources systems around the world and which are the focus of this thesis, namely a desire to:

- Explore new and possibly better operating rules. It is worth noting that in the case of the review project a base case operating plan was used to provide a known reference point for the purposes of comparing alternative operating plans.

- Consider more than two or three broad objectives by taking explicit account of all major interests for water, particularly social interests such as for the provision of recreation amenity.
- Adopt sustainability principles in the development of a shared vision for the operation of systems.
- Adopt trusted simulation models to assist in evaluating system performance under alternative operating plans.

It is worth noting that unlike the review project, this thesis considers climate change a fundamental component of all water resources planning studies.

1.5 Innovations of the research

There are two major innovations to this research, viz; (i) the structured multi-objective optimisation procedure; and (ii) the analytical approach for evaluation of candidate optimal operating plans. Note that whilst the term *operating plan* is used in this section, both innovations are relevant to the development of any water resources management plan that may be of interest to the DM.

The novelty in the structured multi-objective optimisation procedure is that assists the DM to develop a shared vision for the operation of complex water resource systems by incorporating a greater level of realism into the decision-making process. Limiting water resources problems to two or three objectives overlooks the complexities associated with the many conflicting interests for water, the complex rules which control the movement of water, and the hydro-climatic processes that affect the availability of water resources. The structured multi-objective optimisation procedure achieves this greater level of realism through, both, a holistic approach of formulating the problem and the use of O-S modelling. The problem formulation approach sets out a flexible basis on which to establish an overall goal for the water resources system and to set out the underlying individual goals of the various interests for water. Structuring the problem in this way provides the solid foundations for the evaluation of candidate optimal operating plans (described in the second innovation below). The O-S modelling approach allows for the incorporation of complex operating rules and the latest advances in future climate projections through the use of trusted simulation model. Additionally, the optimisation model that is linked to this simulation model provides an efficient and effective means to conduct a far reaching or *global* search for candidate optimal operating plans. Moreover, the problem formulation approach provides the vital link between the individual interests for water and the search for candidate optimal operating plans. All these attributes (of the multi-objective optimisation procedure) provide the necessary structure, flexibility, and transparency in the decision making process to engage stakeholders and DMs and to provide them with the basis of meaningful dialogue for solving real-world water resources planning problems (i.e. higher order MOOPs).

The novelty in the analytical approach which has been developed to evaluate candidate optimal operating plans is that it provides a visual means to communicate O-S modelling results for higher order MOOPs, in both the objective space and decision space. This analytical approach builds on the proven capabilities of a sustainability index developed and refined by Loucks (1997), Loucks and Gladwell (1999), and Sandoval-Solis et al. (2011). Importantly, this Sustainability Index (SI) is capable of quantifying sustainability by combining various performance metrics to represent the reliability, resiliency, and vulnerability of water resources systems over time. In terms of the objective space, ranking and plotting the SI against its normalised rank provides a visual representation of the Pareto front. The gradient of the SI curve represents the diversity of the operating plans with respect to the objective space. A larger gradient represents operating plans that are more diverse than those that produce a section of curve with a smaller gradient. In terms of the decision space, the corresponding decision variable values may be plotted together with the SI curve to inform the DM about how different planning decisions influence a system's sustainability.

These two major innovations combine the formation of Pareto fronts for a range of hydro-climatic conditions with sustainability principles to deliver a practical tool that can be used to evaluate and select preferred Pareto-optimal solutions of higher order MOOPs for any water resources system. Such innovations have the potential to set a new precedent in the way operating plans are developed and reviewed over time.

1.6 Layout of this thesis

This first chapter provides an insight into water resources systems with regards to the conflicting interests for water, complex operating rules, and how they are affected by changes in system configuration and changes in climate. It describes the significance of the research in terms of the need for optimising the operation of water resources systems and proposes a structured procedure for the development of a shared vision for the operation of water resources systems. It also presents the aims of the study and describes the tasks undertaken to achieve these aims.

The second chapter presents a critical review of the literature on multi-objective optimisation modelling in water resources planning. It describes the many challenges that exist in the optimisation of water resources systems such as the need to explicitly account for conflicting interests for water and the need to develop new and possibly better ways to operate these systems under a range of hydro-climatic conditions. Moreover, it discusses the challenges in visualising the Pareto front and in trading off optimal solutions in higher order MOOPs.

The third chapter describes a structured procedure which is aimed at assisting the decision maker (DM) to develop a shared vision for the operation of water resource systems considering climate change. It deals with identifying all the major interests for water in a complex water resource system; the formulation of a MOOP that takes explicit account of all the major interests for water in the system; the set up of the O-S model used to solve for this MOOP; and the indices used to analyse and select a preferred optimal operating plan subject to stakeholders' preferences.

The fourth chapter presents an approach for analysing Pareto-optimal operating plans using the proposed multi-objective optimisation procedure assuming historical hydro-climatic conditions. It presents an analytical approach that deals with ranking alternatives; assessing the level of influence that a set of operating rules has on a system's sustainability; and with showing the effect of alternative operating plans on various interests for water.

The fifth chapter applies the analytical approach presented in the fourth chapter to MOOPs considering two plausible future greenhouse gas (GHG) emission scenarios. It deals with evaluating and comparing the optimal operating plans that were found under historic hydro-climatic conditions (in the fourth chapter) against the optimal operating plans under the two GHG emission scenarios. It also deals with selecting the most preferred optimal operating plan(s) by incorporating stakeholders' preferences.

The sixth chapter summarises this thesis, the main conclusions and recommendations for future work.

Chapter 2. Multi-objective optimisation modelling in water resources planning - a review

2.1 Introduction

This chapter presents a critical review of the literature on multi-objective optimisation modelling in water resources planning. Specifically, it deals with (i) the various aspects of water resources planning and the multi-criterial nature of problems concerning the planning and operation of multi-purpose, multi-reservoir water resources systems; and (ii) multi-objective optimisation as a means by which to solve such complex problems by finding new and possibly better ways to operate water resources systems, particularly in an uncertain climate future. For this purpose, reference is made to the Wimmera-Glenelg Water Supply System (WGWSS) case study which is located in north-western Victoria (Australia). The WGWSS is a multi-purpose, multi-reservoir system which is managed through a complex regime of operating rules to meet a range of interests for water (Godoy et al., 2009).

Water resources systems are operated for many uses such as municipal water supply, irrigation, hydro-electric power generation, flood mitigation, and storm drainage (Linsley et al., 1992). These systems also play an important social role in providing recreational amenity and as a place of cultural and spiritual significance (GWMWater, 2012a; 2012b). Optimal operation of water resources systems requires careful planning in order to ensure that the intended benefits are realised (Labadie, 2004). In many countries around the world, water resources planning occurs at the national level in terms of broad goals which are translated into regional actions (Linsley et al., 1992; Castelletti and Soncini-Sessa, 2006; NWC, 2014). Present day water planning processes around the world highlight a desire to move towards sustainable operating plans that explicitly incorporate all interests for water and which find an optimal solution or, at best, a compromise solution amongst all these water needs (Loucks and Gladwell, 1999). Importantly, it has been confirmed that carbon dioxide (CO_2) was the major anthropogenic greenhouse gas (GHG) contributing to the warming of the global climate system (IPCC, 2007). Fortunately, the availability of general circulation models (GCMs) makes it possible for planning processes to incorporate the latest advances in the projection of future climate. GCMs are based on the theories of atmospheric physics. Such hydro-climatic data can be incorporated into simulation and optimisation models to examine the potential impacts of changes to not only hydrological conditions, but also changes to infrastructure and operating rules without incurring the costs and risk that would be incurred if such changes were to happen to in practice (Palmer et al., 1999). Refer to Section 2.2 for details of this part of the study.

Many of the interests for water in water resources systems are conflicting and non-commensurable which can be generally reduced to multi-objective optimisation problems (MOOPs). Characteristically, these problems give rise to a set of optimal solutions referred to as *Pareto-optimal* solutions or the *Pareto front*, instead of a single optimal solution (Deb, 2001). A general MOOP consists of a number of objectives subject to a number of inequality and equality constraints (Srinivas and Deb, 1995). Classical and non-classical multi-objective optimisation methods are described in this chapter and the advantages and disadvantages of using these methods are discussed in terms of their ability to search for candidate optimal solutions in high-dimensional problems. In recent times there has been growing interest in using evolutionary algorithms (i.e. non-classical multi-objective optimisation methods) given that these optimisation methods can be directly linked with trusted simulation models (Labadie, 2004). Note that in this thesis such models are referred to as optimisation–simulation (O-S) models. Various O-S models applications are also presented highlighting the extent to which these reflect real-world water resources systems. Moreover, the challenges associated with the setting up of the optimisation engine and the simulation engine of an O-S model are described. The difficulties with solving higher order MOOPs are also presented in terms of the available techniques used to visualise the Pareto front, and to address the issue of slow convergence to the Pareto front. The issue of slow convergence to the Pareto front is described and various techniques including the use of larger population sizes are discussed. With respect to selecting a preferred optimal solution from the Pareto front of high-dimensional problems, multi-criteria decision analysis (MCDA) techniques are presented as a means to develop a conceptual model which can be used to represent stakeholders' preferences and value judgements. Refer to Section 2.3 for details of this part of the study.

2.2 Water resources planning

2.2.1 Water resources systems

As part of the process of finding optimal or compromise solutions, there are a number of challenges that exist in the planning of water resources systems. This section describes the national and regional planning processes that exist around the world and highlights two important challenges which are relevant to the aims of this study, namely the need to (i) consider more than two or three broad objectives by taking explicit account of all major interests for water; and (ii) to incorporate the complex set of operating rules which control the movement of water within water resources systems.

Water is controlled and regulated to serve a diverse range of purposes (Linsley et al., 1992). In applications such as flood mitigation and storm drainage, water is controlled to minimise damage to property, inconvenience to public, or loss of life. In other applications such as for municipal water supply, irrigation, and hydro-electric power generation, water may need to be regulated through a system of headwork and balancing storages, and distributed through a network of open channels and/or pressurised pipeline. Additionally, water also plays an important social role in providing recreational amenity and the cultural and spiritual development of people all around the world. Despite this diversity in the dependency on water, the collection of natural assets and artificial structures used to control and regulate water has been commonly referred to as *water supply systems* (Linsley et al., 1992). More recently however, the term being used by water practitioners and academics is *water resources systems*; given that the planning and management of such systems has a wider range of beneficial uses (Loucks and Gladwell, 1999; GHD, 2011; GWMWater, 2012a).

Since the 1960s there has been an increasing concern about the environment given an uncontrolled population growth and production of waste which threatens the quality of air, land, and water (Linsley et al., 1992). This development of civilization has increased the importance of water resources management, not only for potable and irrigation purposes but also for public health reasons. Modern standards in personal hygiene require significantly more water than was used a century ago. The increase in population has increased the acreage required for agriculture and the need for irrigation and drainage systems. The increase in industrial development has meant that water is often used for processing food and for hydro-electric power generation.

Such is the damage that is being caused by this development of civilization, that increasing numbers of flora and fauna are becoming endangered and extinct around the world.

Management of the natural forces of precipitation, evaporation, and streamflow requires the collection, drainage, and transfer of water with consideration to varying scales both spatially and temporarily; particularly in multi-reservoir systems. Reservoir operation is a complex and challenging decision problem, not only because of the presence of multiple conflicting objectives but also owing to seasonal and stochastic variations in the demand for and supply of water. Typical objectives may include satisfaction of demands for water supply and for in-stream environmental flows; maximising flood mitigation, hydro-electric power generation, and recreation amenity; and protecting cultural heritage etc (Agrell et al., 1998; Emsconsultants, 2009; GWMWater, 2012a; VEWH, 2013).

Decision variables for reservoir operation typically include flow rates and upper limits of harvest/release and storage levels throughout the year. The seasonal aspect of reservoir operation is not restricted to system inputs and outputs, since the operational decisions are often closely related to seasonal activities and events. In one example for the Shellmouth Reservoir in Manitoba (Canada), a release decision in January to meet the demand for hydroelectric power generation may differ from the trade-off between power supply and recreational benefits in July, when fishing and tourism are at their peaks (Agrell et al., 1998). In another example for the WGWSS in western Victoria (Australia), the inter-storage transfer decision from Rocklands Reservoir to Toolondo Reservoir is an important consideration with regards to minimising uncontrolled spills to the Glenelg River in winter/spring and minimising supply deficits to consumptive users and the in-stream environment all year round (GHD, 2011; GWMWater, 2012a; VEWH, 2014).

An incentive to undertake formal planning and analysis is that the investments and long-term consequences of water resource decisions are often large in terms of time and money expended (Agrell et al., 1998). Operation of water resources systems requires effective planning to ensure that the intended benefits are realised (Labadie, 2004). Mooney et al. (2012) pointed out that it is important to properly identify interests and values in the water planning decision-making process. Planning for water resources purposes may be defined as:

> "...*the orderly consideration of a project from the original statement of purpose through the evaluation of alternatives to the final decision on a course of action*." (Linsley et al., 1992, p777)

Planning occurs at many levels within each country with a differing of purpose and planning effort at each level. Many countries have a national planning organisation with broad objectives to enhance economic growth and social conditions within the country. Whilst the national planning organisation may not deal with water matters directly, the goals it sets in terms of production of food, energy, housing etc may require specific targets for water management. In most countries there are several agencies that are responsible for specific areas of water management. In order to bridge the national planning effort and the many water agencies, some countries have formed groups that help co-ordinate water planning so that common methodologies are established allowing for comparisons between various project studies. The U.S. Water Resources Council, the Venezuelan Commission for Planning of Hydraulic Resources, the European Commission, and the Australian National Water Commission are some examples (Linsley et al., 1992; Castelletti and Soncini-Sessa, 2006; NWC, 2014).

Moreover, the broad objectives set at the national planning level have placed a greater focus on sustainability in recent times. For example in 1980 the U.S. national objectives were to enhance national economic development and enhance the quality of the environment (Linsley et al., 1992). By comparison, the Australian national objectives were aimed at delivering nationally compatible water entitlements; conjunctive management of surface water and groundwater resources; and risk assessments associated with changes in future water availability (NWC, 2014). This more recent approach, which has been adopted by many countries around the world, is based on the concept of *sustainable development* which is discussed in greater detail in Section 2.2.2.

In order to delineate the planning efforts between the various regions of a country, regional planning groups may be set up to establish regional planning processes. As specific actions in water management are likely to have consequences both upstream and downstream, such groups are responsible for co-ordinating the various activities and planning efforts within the river basin or water catchment. Examples of such regional planning groups are the Spanish Basin Agencies (Confederaciones

Hidrograficas) and the Victorian catchment management authorities (CMAs) in Australia (Andreu et al., 2009; VEWH, 2014). The Wimmera CMA and the Glenelg-Hopkins CMA are responsible for co-ordinating such activities in the WGWSS. The broad national planning goal to improve environmental conditions has been translated into 18 watering actions which are specifically aimed at protecting platypus, freshwater catfish, Wimmera bottlebrush and other riparian vegetation in the WGWSS (VEWH, 2014). Linsley et al. (1992) pointed out that planning of specific actions such as these is the lowest level of planning and it is this level that determines the effectiveness of water resources management.

Another example of a regional planning process concerning the WGWSS was the development of the Western Region Sustainable Water Strategy (DSE, 2011) which was aimed at:

> "....*providing increased certainty to water users and the environment; promoting sustainable water use; and protecting and improving the health of waterways, aquifers, wetlands and estuaries*..." (DSE, 2011, p52)

An important action under the strategy was to undertake periodic reviews of the water sharing and operating arrangements of the WGWSS. The first review was completed in 2014 and the outcomes of the study showed that after three years of implementing the bulk water entitlements; management of the system was in line with the stated objectives (GWMWater, 2014). The review was supported by simulation modelling over a long-term planning period assuming historic and future hydro-climatic conditions which are discussed further in Section 2.2.3.

2.2.2 Moving towards sustainability

The development and management of water resources systems is a fundamental component of *sustainable development*. Loucks and Gladwell (1999) argued that sustainable development could only succeed with sustainable water resources systems supporting that development. In their review of the many definitions of *sustainable development*, they proposed the following definition for the management of water resources systems:

"*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*." (Loucks and Gladwell, 1999, p30)

Whilst the concept of sustainability has become a common theme in water resources planning over the last decade, present day planning processes are challenged by a number of factors including (i) a top-down planning focus which does not always provide a link between the broad national goals and the diverse range of interests for water at a local scale; and (ii) the incorporation of interests for water that are not easily quantifiable such as those that provide a social benefit in water resources systems.

Water resources planning processes which have a top-down focus usually have broad national goals enshrined in international directives and statutes which planners are obliged to follow. Two studies which have set out to propose an alternative to this top-down approach are those undertaken by Castelletti and Soncini-Sessa (2006) and Graymore et al. (2009).

Castelletti and Soncini-Sessa (2006) proposed a nine-step participatory and integrated water resources planning procedure as a move forward to address the lack of communication between scientists and policy-makers, and applied it to a real-world planning process as part of a multi-objective decision support system (DSS). The water resources system comprised Lake Maggiore; a natural lake located south of the Alps between Italy and Switzerland which is operated to supply downstream irrigation, the in-stream environmental requirements of the River Ticino, and for hydropower generation. Additionally, the lake is also operated to mitigate flood events which have had a disastrous effect on the lake coastline population in 1993 and 2000. The outcomes of their application resulted in nine compromise alternatives representing different combinations of structural actions (e.g. dredging the lake outlet), normative actions (e.g. changes to release rules at the operator's discretion), and regulatory actions (e.g. release rules which must be followed by the operator). Castelletti and Soncini-Sessa (2006) claimed that the compromise alternatives were likely to have been considered as part of (then) negotiations under the Italian-Swiss agreement of 1943 given that there was strong support by stakeholders from both countries. It is worth highlighting that many researchers agree that DSSs are an effective means to overcome the hindrances of multi-objective optimisation due to the ability of such systems to place the responsibility for the success or failure of system operation on operators and water managers rather than overly empowering computer analysts (Labadie, 2004).

Building on the concept of DSSs, Graymore et al. (2009) suggested that a sustainability assessment at the regional scale provided the necessary link between top-down national goals and bottom-up local actions in order to help preserve the "...*ecosystem goods and services* ..." for future generations. The authors developed a sustainability assessment framework for regional agencies in south west Victoria (Australia) by using a DSS which was linked to a Geographical Information System (GIS). This tool was used to prepare maps showing sub-catchment sustainability levels in terms of the condition of environmental, social, and economic indicators. These maps were able to highlight those areas most in need of assistance for achieving sustainability. Graymore et al. (2009) further suggested that the tool would be able to show variations in sub-catchment sustainability by way of repeating the assessment process each year. The authors claimed that such information could be used by regional water agencies as part of planning processes that were aimed at improving regional sustainability over time.

However whilst such studies by Castelletti and Soncini-Sessa (2006) and Graymore et al. (2009) have demonstrated the positive steps being made on the sustainability front, one area that continues to require attention is the social assessment of water resources management options. Mooney et al. (2012) reported on several tools they had used to identify interests and values of water by undertaking a social impact study of water users in South Australia and Queensland. Similar to Castelletti and Soncini-Sessa (2006), Mooney et al. (2012) also used a participatory approach with the aim of understanding users' preferences and values in water allocation deliberations. Mooney et al. (2012) argued that undertaking such assessments early in a decision-making process improved the potential to influence the outcomes of planning processes by integrating the assessment of management options into community engagement.

2.2.3 Future climate considerations

An important consideration in water resources planning is the need for data; most of which represents current conditions such as land use, population, available water etc. Additionally as water resources planning is for the future, forecasts of future conditions are essential (Linsley et al., 1992). This is especially true in planning studies that have a long-term planning period often 50 to 100 years into the future. Fortunately, the availability of GCMs makes it possible for planning processes to incorporate the latest advances in the projection of future climate. In the context of the present study, such advances have the potential to provide a better understanding of which operating rules are paramount in terms of the sustainability of water resources systems.

In terms of forecasts of future conditions, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) stated that:

> "....*the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*." (IPCC, 2007, p2)

The Fourth Assessment Report explained that the carbon dioxide (CO_2) was the most important anthropogenic GHG and that annual emissions increased by about 80% between 1970 and 2004. The Fourth Assessment Report compared the long term trends against corresponding data under the IPCC's previous report i.e. the Third Assessment Report (IPCC, 2001). Such comparisons showed that the average surface temperature had increased from 0.6 ºC to 0.74 ºC and that the increase was widespread over the globe; greater at higher northern latitudes. The data also showed that global average sea level had increased at an average rate of 1.8 mm/yr and 3.1 mm/yr since 1961 and 1993 respectively. Moreover, snow and ice covered areas had shrunk by an average of 2.7% per decade with the largest decrease in summer. Whilst precipitation over the period 1900 to 2005 had increased significantly in eastern parts of North and South America, and northern parts of Europe and Asia; there had been a decline in the Mediterranean, and southern parts of Africa and Asia. Given these hydro-climatic changes, there was a high degree of confidence that there would be an increase in annual runoff and water availability at high latitudes and a decrease in some dry regions in the mid-latitudes and tropics by the mid-21st century. Moreover the projections indicated that such hydro-climatic changes would intensify water security problems in southern and eastern Australia by 2030 (IPCC, 2007).

The Australian Academy of Science (AAS) examines the climate change science with a focus on the impacts to Australia. According to AAS (2010), the average surface temperature has increased by about 0.7 ºC since 1960 causing a nation-wide average increase in the frequency of extremely hot days and a decrease in the frequency of cold days. The long term trends in rainfall showed a significant increase over north-western Australia, and deceases over south-western and south-eastern Australia since 1960. Importantly, these climatic changes over south-east Australia provided conditions that were conducive to fire which among other impacts may cause water quality problems in water resources systems. Projections showed that temperatures in Australia were likely to be 0.5 ºC or higher by 2030 as compared to 1990 levels and that the frequency of hot days and nights would increase (AAS, 2010).

In terms of the latest advances in the projection of climate into the future, GCMs are widely considered to be the most advanced tools available (Anandhi et al., 2008). These global climate projections are based on assumed future GHG emission scenarios (IPCC, 2000). However, the coarse spatial resolution of GCMs does not allow for predictions at the catchment or local scale and so they are incapable of producing outputs at the fine spatial resolution needed for most hydrological studies. To address this issue, downscaling methods have been developed which link coarse resolution GCM outputs to surface climatic variables at finer resolutions. Downscaling techniques can be broadly classified as either dynamic or statistical. Both techniques have their advantages and disadvantages but one important factor to consider is that dynamic downscaling has higher computational costs owing to its high complexity compared to statistical downscaling methods (Sachindra et al., 2012).

Sachindra (2014) developed various models for the purposes of statistically downscaling coarse atmospheric data to produce rainfall, evaporation, and streamflow data sets at the catchment level. The atmospheric data was sourced from the outputs of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the Hadley Centre Coupled Model version 3 General Circulation Model (HadCM3) given that these produced the best calibration and validation results (Sachindra et al., 2014a). Moreover, these GCM outputs were corrected for any bias using the tested procedure developed by Sachindra et al. (2014b). To derive projections of global climate into the future, these GCMs are fed data inputs that correspond to a range of concentrations of atmospheric GHGs according to *storylines* that describe different levels of development in terms of demographic, socio-economic and technological change into the future (IPCC, 2000). Anandhi et al. (2008) suggested that a proper assessment of probable future climate and its variability ought to be made based on various climate scenarios and so it is preferable to consider a range of scenarios in climate impact studies in order to better reflect the uncertainties of possible future climate.

Despite such advances in the projection of hydro-climatic conditions into the future, water resources planning processes for the WGWSS have not incorporated these climate projections. As explained in Section 2.2.1, the opportunity for the inclusion of these latest advances was available as part of the development of both the Western Region Sustainable Water Strategy (DSE, 2011) and the subsequent review of the water sharing and operating arrangements for the WGWSS (GWMWater, 2014). Both these planning studies were supported by simulation modelling over a long-term planning period assuming historic hydro-climatic conditions and two future hydro-climatic conditions. In so far as the future hydro-climatic data sets are concerned, these were referred to as the “continuation of low flow” and the “2030 climate change” conditions.

The continuation of low flow conditions assumed that the flows for all streams in the WGWSS over the period January 1891 to June 1997 were factored down by the ratio of the average streamflow over the period July 1997 to June 2009 to the average streamflow over the period January 1891 to June 2009. This worked out to a 75% reduction in the total average annual inflow for the WGWSS compared to the historic hydro-climatic conditions. Jones and Durack (2005) developed the 2030 climate change conditions using mean global warming estimates for the year 2030 provided by GCMs. Note that unlike Sachindra (2014), Jones and Durack (2005) did not downscale the coarse atmospheric data to the catchment level. Instead Jones and Durack (2005) used a method that assessed the hydrological sensitivity of catchments to climate change using mean global warming estimates for the year 2030 (as provided by GCMs). Jones and Durack (2005) argued that their methodology provided an estimate of the range of change in mean annual runoff which was indicative of “.... *the direction and magnitude of possible changes to water supply*.” Godoy and Barton (2011) estimated that the 2030 climate change conditions represented a 17% reduction in the total average annual inflow for the WGWSS compared to the historic hydro-climatic conditions.

2.2.4 Systems analysis techniques

Water resources planning studies are usually supported by simulation and optimisation models which allow the examination of the potential impacts of changes to hydrological conditions, infrastructure and operating rules without incurring the costs and risks that would be incurred if such changes were to happen to in practice (Palmer et al., 1999). Simulation models attempt to represent all the major characteristics of a system and are tailored to examine "what if?" scenarios (Palmer et al., 1999). Simulation modelling is widely used internationally to evaluate the performance of regulated river basins (Perera et al., 2005; Kuczera et al., 2009). On the other hand, optimisation models are characterised by a numeric search technique and are better suited to address "what should be?" questions. Of particular relevance to this thesis, is the use of combined optimisation–simulation models given that optimisation methods can be directly linked with trusted simulation models (Labadie, 2004).

Labadie (2004) refers to simulation models as descriptive models which help answer "what if?" questions regarding the performance of alternative operational strategies. System operators are generally accepting of simulation models and understand their outputs because the interpretation of results is intuitive (Labadie, 2004). Examples of these include MODSIM (Labadie et al., 1986), WASP (Kuczera and Diment, 1988), WATHNET (Kuczera, 1992), SWAT (Arnold et al., 1999), and REALM (Perera et al., 2005). In Victoria (Australia) there has been heavy reliance on REALM to support water allocation decisions by way of quantifying the impacts of proposed operational policies on water users' allocations (Kularathna et al., 2011; Godoy Consulting, 2014; GWMWater, 2014). REALM is a structured computer software package that models the harvesting and bulk distribution of water resources, usually at monthly time-steps, within a water resources system (Perera et al., 2005). It has been developed in close consultation with water managers and practitioners with many improvements made in response to feedback from these users. As it has also undergone extensive testing and has been used in many practical applications, it is considered to be the modelling standard in Victoria. The states of Western Australia and South Australia are also major users of REALM.

Perera et al. (2005) described the REALM setup including the preparation of input files and the system file representing the water supply network, and the modelling output and utility programs available for post-processing. With the aid of a graphical user interface, the water supply network is developed using *nodes* representing stream junction points, reservoirs, and water demands which are connected with *carriers* which represent waterways, channels and pipes as required. At each simulation time-step, REALM converts the network of nodes and carriers into a generic network which is able to be solved by a network linear programming algorithm called RELAX (Bertsekas, 1991). Like other network linear programming software, RELAX uses an objective function that minimises the sum of flow multiplied by penalty in the network to obtain optimised carrier flows while not exceeding carrier capacity constraints and maintaining flow balance at the nodes.

Siriwardene and Perera (2006) characterise optimisation methods as being either deterministic or stochastic. Linear programming and dynamic programming can be used in either of these two approaches. Deterministic methods are able to efficiently solve large-scale optimisation problems but their main disadvantage, in so far as is described in this thesis, is that these are unable to handle *many-objective* (or *higher order*) problems where three or more objectives are optimised simultaneously. Stochastic methods are designed to work directly on probabilistic descriptions of random rather than deterministic hydrologic sequences. Whilst stochastic methods cannot guarantee termination to optimal solutions they are often capable of undertaking a more far reaching or *global* search for optimal solutions where deterministic methods would either fail to converge or get stuck in local optima (Labadie, 2004). In terms of the stochastic approach, heuristic programming models are based on rules-of-thumb, experience or various analogies applied to quantitative and qualitative information (Labadie, 2004).

One of the fastest growing areas within the heuristic programming field is the use of multi-objective evolutionary algorithms. The reason for this is that these are robust and can solve highly non-linear, non-convex problems. Additionally since evolutionary algorithms are population-based searches means that these are amendable to be implemented on distributed or shared memory parallel computing architectures which has become an important way of reducing application run times, increasing the size and difficulty of applications (Goldberg, 1989). Arguably, the most popular of the evolutionary algorithm family is the genetic algorithm (GA) which uses a process analogous to the biological processes of natural selection i.e. reproduction, crossover, and mutation (Nicklow et al., 2010). Examples of these include the Pareto-Archived Evolution Strategy (PAES) developed by Knowles and Corne (1999); the Strength-

Pareto Evolutionary Algorithm (SPEA2) developed by Zitzler et al. (2001); and the more widely used Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) developed by Deb et al. (2002). Despite these theoretical advances, the lack of popularity in optimisation models has been largely due to the fact that these models are more complex to develop and have greater computational requirements than simulation models. As a consequence, problems that have used optimisation modelling have tended to be simplified in comparison to those developed for simulation models (Labadie, 2004).

The attraction to using *prescriptive optimisation* models is that optimisation methods can be directly linked with trusted simulation models without requiring simplifications in problem specification (Labadie, 2004). Note that in this thesis such models are referred to as optimisation–simulation (O-S) models. These O-S models have the ability to undertake an efficient and effective search for candidate optimal solutions in complex water resources problems (i.e. higher order problems) and to simulate the behaviour of complex water resources systems (i.e. multi-purpose and multi-reservoir systems) under the influence of such candidate optimal solutions. With respect to the many challenges facing water resources planning presented in Section 2.2, O-S models would appear to, at least in theory, be able to handle a range of complex issues in real-world water resources problems. Section 2.3.2 further describes the use of O-S models in the context of MOOPs.

2.3 Multi-objective optimisation

Water resources systems are managed and operated for the benefit of a range of interests including consumptive users, for recreation and cultural purposes, and the environment. Many of these interests for water are conflicting and non-commensurable which can be formulated as MOOPs. Characteristically, MOOPs give rise to a set of optimal solutions, instead of a single optimal solution as in single-objective optimisation. Note that single-objective optimisation involves only one objective function (Deb, 2001). It is important to highlight that the focus of this thesis is on MOOPs as distinct from single-objective optimisation problems. A general MOOP consists of a number of objectives subject to a number of inequality and equality constraints. Mathematically, the problem may be written as follows (Srinivas and Deb, 1995):

Minimise/Maximise	$f_i(x)$	$i = 1,2,\ldots, I$	
Subject to	$g_j(x) \leq 0$	$j = 1,2,\ldots, J$	
	$h_k(x) = 0$	$k = 1,2,\ldots, K$	(2.1)

The parameter x is a p dimensional vector having p design or decision variables. The aim is to find a vector x that satisfies J inequality constraints, K equality constraints and minimises/maximises the I objective functions (Srinivas and Deb, 1995). Solutions to MOOPs are mathematically expressed in terms of superior or *non-dominated* points. This highlights the difficulty with MOOPs in that there is usually no single optimal solution with respect to all objectives, as improving performance for one objective means that the quality of another objective will decrease. Instead there is a set of optimal trade-offs between the conflicting objectives known as the *Pareto-optimal* solutions or the *Pareto front* (Deb, 2001). In the case of a sample MOOP that seeks to (i) minimise the supply deficit or shortfall in supply to an environmental water demand (EWD); and (ii) to minimise the amount of water released to the EWD from an upstream storage, conflict among these two objectives would generally arise in a situation when there is a high degree of competition for water i.e. during a water shortage. Figure 2.1 is a graphical representation of this sample two-objective minimisation-minimisation (min-min) MOOP.

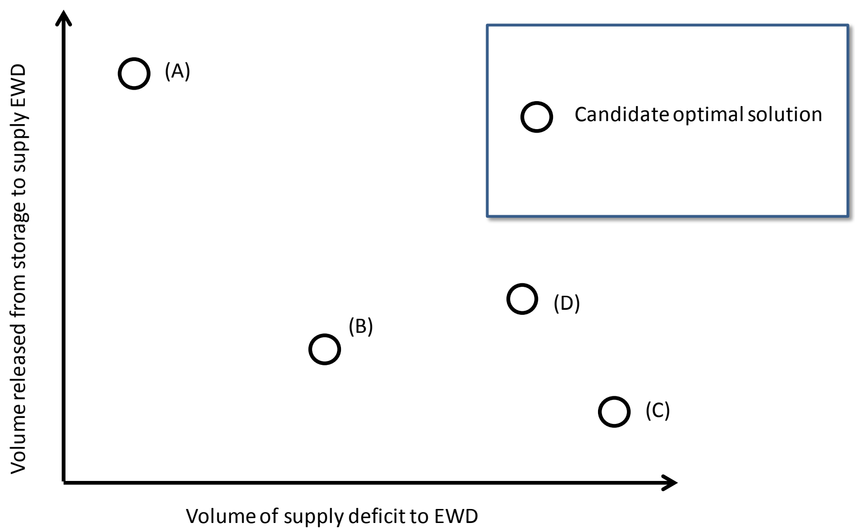


Figure 2.1 Sample min-min multi-objective optimisation problem

The figure shows that the x-axis refers to the volume of supply deficit of the EWD and the y-axis refers to the volume released from the storage to supply the EWD. Each of the four candidate optimal solutions, Solution (A) to Solution (D), shown in Figure 2.1 have two objective values associated with it. Note that these solutions are for illustration purposes.

Identifying the non-dominated set of solutions from a given set of solutions is similar in principle to finding the minimum of a set of real numbers. In the latter case, two numbers are compared to identify the smaller number using the '$<$' relation operation. In the former case, a solution (x_1) is said to dominate the other solution (x_2), if both of the following conditions of the dominance test are true:

i. Solution (x_1) is no worse than solution (x_2) in all objective functions; and
ii. Solution (x_1) is better than solution (x_2) in at least one objective function. (2.2)

If any of the above conditions are violated, solution (x_1) does not dominate solution (x_2). There are three outcomes of this dominance test, namely solution (x_1) dominates solution (x_2); solution (x_1) is dominated by solution (x_2); or solution (x_1) and solution (x_2) do not dominate each other and are said to belong to the Pareto front. Figure 2.2 shows the same solutions shown in Figure 2.1 except that the results of the dominance test are shown by way of colour-coding, being blue shade for the set of non-dominated

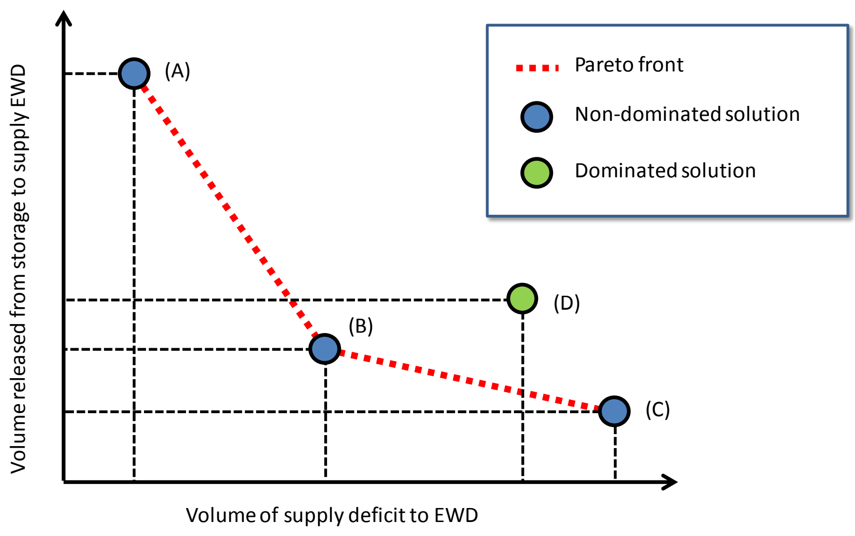


Figure 2.2 Sample min-min multi-objective optimisation problem (with colour-coding to show the dominance test results)

solutions (i.e. Pareto-optimal solutions); and green shade for the dominated solutions.

For the purposes of demonstrating the application of the dominance test in Equation 2.2, the classifications of Solution (A) to Solution (D) are determined as follows:

- Comparing Solution (A) to Solution (B) shows that Solution (A) does not dominate Solution (B) because it violates condition (i) of Equation 2.2 in that Solution (A) is worse than Solution (B) with respect to the volume released from storage to supply the EWD. In fact, Solution (A) does not dominate any of the three other solutions for the same reason. At this stage the classification of Solution (A) cannot be confirmed without further testing as given below.
- Comparing Solution (B) to Solution (A) shows that Solution (B) does not dominate Solution (A) because it violates condition (i) of Equation 2.2 in that Solution (B) is worse than Solution (A) with respect to the volume of supply deficit of the EWD. Comparing Solution (B) to Solution (C) reveals that Solution (B) does not dominate Solution (C) because it also violates condition (i) of Equation 2.2 i.e. Solution (B) is worse than Solution (C) with respect to the volume released from storage to supply the EWD. However, in comparing Solution (B) to Solution (D), both conditions (i) and (ii) of Equation 2.2 are satisfied and Solution (B) is said to dominate Solution (D). Thus, the classification of Solution (D) as a dominated solution is confirmed by Solution (B) which means that Solution (D) does not belong on the Pareto front.
- Continuing the comparisons for Solution (C) and Solution (D) in the same way confirm the results shown in Figure 2.2.

2.3.1 Classical and non-classical methods

Classical multi-objective optimisation methods combine multiple objectives into one overall single objective function, Z. Perhaps the simplest of these is the *method of objective weighting*, which may be written as follows (Srinivas and Deb, 1995):

$$\text{Minimise/Maximise, } Z = \sum_{i=1}^{N} w_i f_i(x) \text{ , where } 0 \le w_i \le 1 \text{ Note the sum of all weights } w_i \text{ equals } 1 \quad (2.3)$$

In this method the optimal solution is controlled by the weight vector w. As higher level qualitative information is required in order to set a preference for one objective over another, classical methods tend to be highly subjective to the particular user (Deb, 2001). Notwithstanding this potential deficiency, Godoy and Barton (2011) demonstrated that such an approach could be used to find trade-off solutions for the environment's regulated and unregulated entitlement considering a range of hydro-climatic conditions using a simulation modelling.

Non-classical techniques can consider all objectives concurrently in a single run and are not affected by the dimensionality aspect of MOOPs. *Dimensionality* in this context refers to the number of objectives that are considered simultaneously as part of solving the MOOP. Perhaps the most important characteristic of these methods is that unlike classical methods, these tend to have the ability to undertake a more far reaching or *global* search for optimal solutions. Non-classical methods are particularly useful for water resource management problems because they tend to find the entire set of Pareto-optimal solutions which may be used to inform a diverse and often conflicting group of stakeholders whose decisions depend on a number of different factors. Deb (2001) described the ideal multi-objective optimisation procedure as one that involves bringing together quantitative and qualitative information as follows:

> " *Step 1: Find multiple trade-off optimal solutions with a wide range of values for objectives.*
>
> *Step 2: Choose one of the obtained solutions using higher-level information*." (Deb, 2001, p4)

2.3.2 Optimisation-simulation modelling

As explained in Section 2.2.4, researchers generally agree with the use of prescriptive optimisation models given that optimisation methods can be directly linked with trusted simulation models without requiring simplifications in problem specification (Labadie, 2004). Note that in this thesis such models are referred to as optimisation–simulation (O-S) models. Labadie (2004) pointed out that another key reason for the growing interest in O-S models was that the optimisation engine could include a heuristic programming model (e.g. a genetic algorithm (GA)) which has the ability to undertake a global search for optimal solutions and to solve highly non-linear, non-convex problems.

Figure 2.3 illustrates the structure of an O-S model which comprises a GA-based optimisation engine and a simulation engine. As GAs use a population-based optimisation search technique, the O-S modelling process would commence with a random population of solutions (shown as a green shaded circle). The process is iterative; simulation outputs are used to evaluate the performance of the water resources system under the influence of a given candidate optimal solution (i.e. solution's *fitness* value) which are in turn passed to the optimisation engine to find better performing solutions than in previous iterations or *generations*. The O-S model continues to iterate towards a population of Pareto-optimal solutions (shown as a red shaded circle in Figure 2.3) until convergence has been achieved or the stopping criterion has been reached. Many researchers describe this iterative process as one of *searching* or *finding* candidate optimal solutions. The genetic operators (i.e. selection, crossover, and mutation) of the GA are used to perturb the population of candidate optimal solutions in order to create new and possibly better performing solutions compared to those in previous generations.

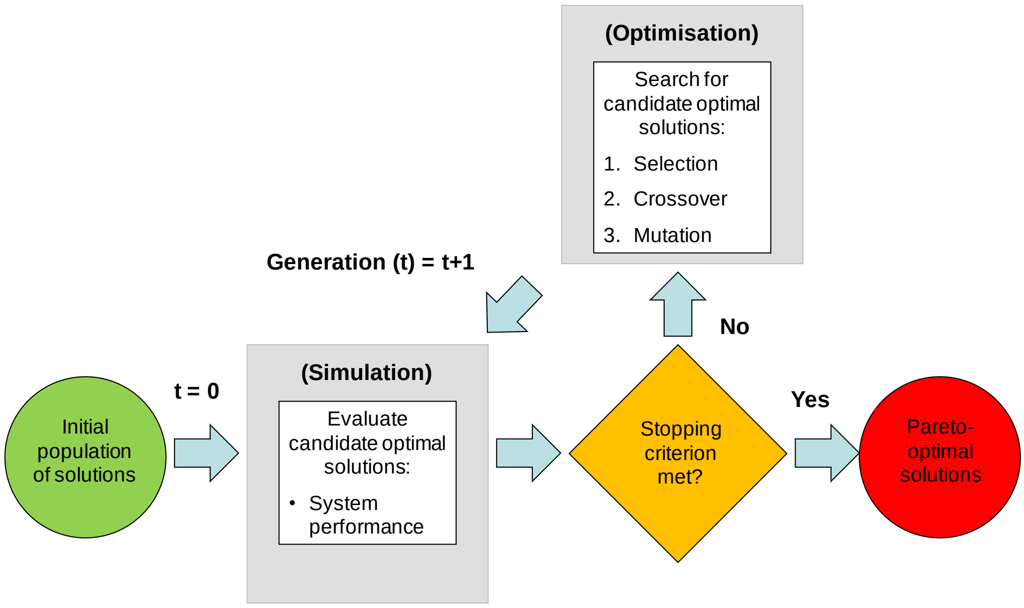


Figure 2.3 Schematic of a GA-based optimisation–simulation modelling approach

The remainder of this section reviews some noteworthy proof-of-concept applications of O-S models which have successfully used a GA-based optimisation engine. Specifically, these applications demonstrate (i) the *fidelity* or degree of realism that can be achieved by such O-S models; (ii) the number of objectives and decision variables that have been used to achieve that fidelity; and (iii) the key study outcomes in each case. Moreover, Sections 2.3.2.1 and 2.3.2.2 highlight the key challenges in regards to the setting up of the optimisation engine and simulation engine.

Bekele and Nicklow (2005) described the use of an O-S model which comprised the U.S. Department of Agriculture's Soil and Water Assessment Tool (SWAT) and the Strength-Pareto Evolutionary Algorithm (SPEA2). This O-S model was applied to a four-objective MOOP, viz.; to (i) minimise the average annual sediment yield; (ii) minimise the annual Phosphorous yield; (iii) minimise the average annual Nitrogen yield; and (iv) maximise the average annual gross margin. The study area was Big Creek, which is a 133 km^2 agriculturally dominated catchment within the Cache River basin located near the confluence of the Mississippi and Ohio rivers (U.S.). The ecological significance of the Cache River basin is largely attributed to the wetland areas which are of international significance (i.e. RAMSAR Wetland). Bekele and Nicklow (2005) adopted three decision variables to represent the cropping decisions associated with land use and tillage practice combinations for each of the 55 sub-catchments of the study area. This equated to a total of 165 decisions which were used to describe an optimal agricultural landscape. The O-S model was executed both at the sub-catchment and catchment level to search for the best trade-off solutions. The study demonstrated the effectiveness of using an O-S modelling approach to quantify the extent to which certain agricultural practices influenced Nitrogen, Phosphorus, and sediment pollution.

Mortazavi et al. (2009) tested the performance of the ε–dominance GA and the ant colony optimisation algorithm using the Canberra Water Supply System (Australia) as the case study. In both cases the algorithms were set up to work with a WATHNET simulation model of the Canberra Water Supply System. WATHNET was developed by Kuczera (1992). Mortazavi et al. (2009) presented a two-objective MOOP, viz.; to (i) minimise present worth cost; and (ii) minimise time spent in restrictions together with 13 decision variables that were used to represent various system configurations and operating rules. The monthly time-step simulation model was run over a period of historic hydro-climatic conditions from 1871 to 2009. Mortazavi et al. (2009) concluded that the GA consistently produced better results and converged faster than the ant colony optimisation algorithm.

Building on their earlier work above, Mortazavi et al. (2012) used the ε–dominance GA and the WATHNET software package to solve several MOOPs relating to the Sydney Water Supply System (Australia). In all cases, the MOOPs were formulated with three objective functions, viz.; to (i) minimise the frequency of restrictions; (ii) minimise the present worth cost of operation and building of new infrastructure; and (iii) to minimise environmental stress on one of many waterways. This time, 11 decision variables were used to represent various system configurations and operating rules. Each MOOP was formulated with the specific aim of addressing three significant shortcomings in the literature. The first related to the maximisation of reliability of supply conflicts with the objectives of minimising cost and environment impacts. In response to this, Mortazavi et al. (2012) used multi-objective optimisation in order to identify trade-offs between these conflicting objectives. The second related to the need to accurately estimate the reliability of supply in supply systems that have a highly reliable supply, particularly during extreme drought in which the probability of triggering drought contingency plans is very small. For this purpose, Mortazavi et al. (2012) generated stochastic hydro-climate data of 500 years and 10,000 years in length for use in their O-S model. The third shortcoming related to the need to search for the best operating rules by considering both short- and long-term operational policies.

Kularathna et al. (2011) used an O-S model which comprised the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) for the optimisation engine and the REALM software package as the simulation engine. This O-S model was used to develop long-term operating plans for the Melbourne Water Supply System (Australia) by solving a three-objective MOOP, viz.; to (i) minimise operating and upgrade costs; (ii) maximise environmental flows; and (iii) to maximise reliability of supply over a 30-year planning period, assuming a monthly simulation time-step. Kularathna et al. (2011) concluded that one of the main advantages of the O-S modelling approach was that it could be directly linked to well-trusted simulation models and that it could be applied to long-term planning periods. The authors also highlighted that one of the key challenges of the O-S modelling approach was in the appropriate formulation of the optimisation problem so that it incorporated key operating rules whilst ensuring problem complexity was maintained at practical levels.

Similar to Kularathna et al. (2011), Godoy et al. (2012) also used an O-S model which comprised the NSGA-II for the optimisation engine and REALM as the simulation engine. This O-S model was used to develop long-term operating plans for the WGWSS by solving a two-objective MOOP, viz.; to (i) maximise the reliability of supply to consumptive users; and (ii) maximise the reliability of environmental flows over a 118-year planning period assuming historic hydro-climatic conditions at a monthly simulation time-step. The operating plan consisted of 29 planning decisions which captured the key operating rules for the system. The O-S modelling results were compared to a base case (simulation-only) operating plan which represented the existing operating plan for the system. The authors demonstrated that there were two Pareto-optimal operating plans found by the O-S model that dominated the base case operating plan.

2.3.2.1 Optimisation engine

Notwithstanding the importance of reviewing multi-objective evolutionary algorithms, the focus of this thesis is the structured multi-objective optimisation procedure and the analytical approach for evaluation of candidate optimal operating plans as described in Section 1.5. To that end, the algorithm adopted for this thesis is not particularly important, other than it being an accepted algorithm that is used by researchers, as is the adopted NSGA-II. Therefore the reader is referred to the works of Zitzler and Thiele (1999), Van Veldhuizen and Lamont (2000), and Deb et al. (2002) for comprehensive reviews of evolutionary algorithms used in multi-objective optimisation.

The importance of the genetic operators and the optimisation parameters in GAs are well established amongst researchers (Zitzler et al., 2000; Deb, 2001; Siriwardene and Perera, 2006; Nicklow et al., 2010). The genetic operators (i.e. selection, crossover, and mutation) are used to perturb the population of candidate optimal solutions in order to create new and possibly better performing solutions compared to those in previous generations. Once the genetic operators have been set up another important challenge lies in specifying the parameters that control the search capabilities of the GA i.e. parameter representation, probability of selection, probability of crossover, probability of mutation, stopping criteria, and population size. For any given MOOP, there is a certain element of design that is required by the analyst in order to fine-tune the modelling outcomes. Nicklow et al. (2010) highlighted the importance of using a carefully designed computational experiment with a clear rationale for the representation, operators, and parameters being used as well as a clear framework for assessing search performance.

Arguably the most common parameter representation used in GAs is in the form of an encoding scheme that transforms the values of decision variables to a structure that permits the genetic operations of selection, crossover, and mutation. Many of these encoding schemes use binary strings (or *chromosomes*) made up of binary 0 and 1 bits (or *genes*). However, Oliveira and Loucks (1997) preferred to use real-valued strings because "......*they provided a more straightforward way of representing the solutions and permitted the design and use of efficient genetic operators that guaranteed the feasibility of the generated solutions*." Moreover to ensure the feasibility of the operating rules, Oliveira and Loucks (1997) designed the GA so that the operators dealt with groups of decision variables which represented one operating rule, rather than with each variable separately. Labadie (2004) highlighted that this issue of parameter representation was one of the continuing challenges in O-S modelling approaches.

The primary aim of the *selection* operator is to make duplicates of good solutions and eliminate bad solutions from a population, while keeping the population size constant. The number of solutions from the population that participate in this selection process is subject to a user-specified probability (i.e. probability of selection). In a review of GA applications in water resources planning and management, Nicklow et al. (2010) stated that the most familiar selection operators available in GA codes were *tournament* selection, *truncation* selection, *roulette wheel* selection, and *Boltzmann* selection. In their review the authors noted that the most modern codes employed a form of tournament and/or truncation selection because these approaches were scaling invariant (i.e. independent from the value range of the objective functions) and elitist (i.e. the best solutions were guaranteed to survive into the next generation). Reed et al. (2000) pointed out that scaling invariance and elitism were important properties that had been shown to improve the effectiveness of GAs in water resources applications.

The creation of new solutions in the population is performed by the *crossover* and *mutation* operators. Additionally, the mutation operator is required in the genetic process in order to maintain diversity in the population. Unlike the selection operator which is applied to the fitness value of the candidate solution, the crossover and mutation operators are applied to the strings of the solution. The number of solutions from the population that participate in the crossover and mutation processes are subject to user-specified probabilities (i.e. probability of crossover and probability of mutation). The distinction between crossover and mutation operators is defined mainly on the number of parent solutions that are required to produce an offspring solution. The crossover operator involves two or more parent solutions where as mutation involves the perturbation of a single parent solution to create a new candidate solution.

Crossover and mutation approaches largely depend on the form in which the strings are encoded in the GA e.g. binary-coded or real-valued GAs (Nicklow et al., 2010). In binary-coded GA applications, Nicklow et al. (2010) referred to theoretical work which showed that *uniform* crossover was often preferred due to its ability to explore new regions in the decision space. Uniform crossover combines the strings of two parent solutions, whereby the parents swap bits at each binary digit. In the case of real-valued GAs, there were two classes of mating operators that were commonly used in water resources applications; namely, *crossover* and *intermediate recombination*. Crossover is analogous to the aforementioned binary string mating approach whereas intermediate recombination combines multiple real-valued parent strings using a variety of statistical averaging and decision variable perturbation schemes. With respect to the mutation operator, binary-coded GA applications commonly employed *jump* mutation or *bit-wise* mutation in which bits in a binary string are randomly changed from 1 to 0 or vice versa. However real-valued GA applications commonly use *Gaussian* mutation in which a vector of real values is used to create a new solution by adding normally distributed perturbations to the decision variables (Schwefel, 1995).

Several studies on the topic of operator and parameter optimisation exist in the literature as highlighted in Zitzler et al. (2000). However the theory behind GAs has provided little guidance on the selection of GA operators even though these operators have a significant impact on GA performance (Schaffer et al., 1989). Given these circumstances, Oliveira and Loucks (1997) used a trial-and-error approach to find a good set of parameter values and to identify the most sensitive ones. In another study, Deb and Agrawal (1999) investigated different GA operator and parameter settings and applied these to problems of varying difficulty. The outcomes of their study showed that simple MOOPs (e.g. unimodel and linear problems) were best solved using the three genetic operators (i.e. selection, crossover, and mutation) with a smaller population size. Deb and Agrawal (1999) referred to these optimisation parameter settings as *selecto-mutation* GAs. Importantly, the selecto-mutation GAs were often not successful in finding the Pareto front of difficult MOOPs (e.g. multimodal and higher order problems. For these difficult MOOPs, Deb and Agrawal (1999) showed that the best optimisation parameter settings had little or no mutation. However, such *selecto-*

recombinative GAs tended to require larger population sizes given that the exploration pressure offered by these parameter settings was reduced (due to the little or no mutation operation).

2.3.2.2 Simulation engine

There are two important considerations for O-S models in terms of the setup of the simulation model, viz; the ability of the simulation model to (i) efficiently run for as many times as is required to converge to the Pareto front; and (ii) have the flexibility to allow for the possibility of a global search for optimal solutions (as is performed by the optimisation engine, refer to Section 2.3.2.1).

Simulation models are considered a first level of abstract representations of physically based systems using mathematical concepts and language, where as *surrogate models* are a second level of abstraction and are computationally cheaper to run than the (original) simulation models (Razavi et al., 2012). Note that the term *original* model is used in this section to refer to the model which represents a first level of abstraction. In a recent review of surrogate modelling in water resources planning, Razavi et al. (2012) explained that there are two broad categories, namely *response surface surrogate* models and *lower-fidelity surrogate* models. Response surface surrogate models use data-driven function approximation techniques to empirically approximate the original model. These are also referred to as *metamodels* and *proxy models* in the literature. Lower-fidelity surrogate models are physically based models but are less detailed compared to the original model. Lower-fidelity surrogate models preserve the main hydraulic/hydrologic processes as modelled in the original model. The authors described all the components involved in the surrogate modelling analysis framework and the various techniques employed in the water resources literature.

Importantly for this thesis, the dimensionality (i.e. number of objectives) of the MOOP is a key factor in the selection of surrogate models. High-dimensional problems have an extremely large search space. Consequently, the number of points required to reasonably represent the search space becomes extremely large, particularly with a higher number of variables as is required in the representation of complex water resources systems. In such cases, response surface surrogate models become less attractive or even infeasible given the large number of points that need to be used to approximate the original model. However, lower-fidelity surrogate models have two distinct advantages as (i) they tend to better emulate unexplored regions of the decision variable space; and (ii) avoid or reduce the aforementioned issues associated with problem dimensionality.

Whilst Razavi et al. (2012) highlighted high computational costs as the main motivation for the use of surrogate models; the other important consideration is whether the original model has the flexibility to allow for the possibility of a global search for optimal solutions. As explained in Section 2.3.2.1, the optimisation engine would be responsible for the creation of new and possibly better performing candidate optimal solutions compared to those in previous generations. In the context of an O-S model which seeks to find optimal operating rules, this would mean that the simulation model is required to change the operating rules to whichever rules are created by the optimisation engine.

2.3.3 Higher order multi-objective optimisation problems

Optimisation studies in water resources management are seldom represented using three or more objectives; the so called *many-objective* or *higher order* multi-objective optimisation problems. The main reason for this is due to the increased difficulty in decision making when the Pareto front cannot be presented geometrically. The effectiveness of data visualisation is based on the fact that about one half of our brain neurons are associated with vision (Lotov et al., 2005). Further, the cognitive capacity of humans has been shown to be limited to holding seven, plus or minus two, digits of information (Agrell et al., 1998; Sinha et al., 2013). From a planning perspective, the limiting of objectives to three has been convenient given the popular sustainability concept commonly referred to as the *triple-bottom-line* (Godoy et al., 2011). Moreover such planning applications, may be considered to be a simplification of real world complexities. However recent multi-objective optimisation applications show there is a growing body of research focused on water resources planning that is seeking to address the challenges associated with higher order MOOPs (Labadie et al., 2010). Of interest to this thesis are the challenges with (i) the visualisation of the Pareto front in terms of the diversity of Pareto-optimal solutions with respect to all objectives; and (ii) the slower convergence of the population of solutions to the Pareto front given the use of the dominance test described in Section 2.3 (refer to Equation 2.2).

Fleming et al. (2005) pointed to the use of *parallel co-ordinates* for the purposes of visualising trade-offs between objectives. Unlike the Cartesian system of having the axes orthogonal to each other (e.g. one objective along the *x*-axis and another objective in the *y*-axis), this approach places all the axes parallel to each other thus allowing any number of objectives to be displayed in a two-dimensional representation (refer to Figure 2.4). Hence, each line in the graph connects the performance objectives acheived by an individual solution of the population. A line (or solution) that crosses another line indicates that the two objectives in question are in conflict, at least in terms of the two intersecting solutions. For instance with reference to Figure 2.4, Solution (A) and Solution (B) are shown in the Cartesian plot (i.e. chart on left) to be located on the Pareto front. The corresponding parallel co-ordinates of these two solutions cause their respective lines to cross each other (i.e. chart on right), confirming that Objective (1) and Objective (2) are in conflict (in so far as these two solutions are concerned). Conversely, lines that do not cross demonstrate that the two objectives are in harmony, at least in terms of the two given solutions. Again with reference to Figure 2.4, all solutions located on the Pareto front are shown to have parallel co-ordinates that cause their respective lines to cross each other thereby confirming that Objective (1) and Objective (2) are in conflict with respect to all solutions.

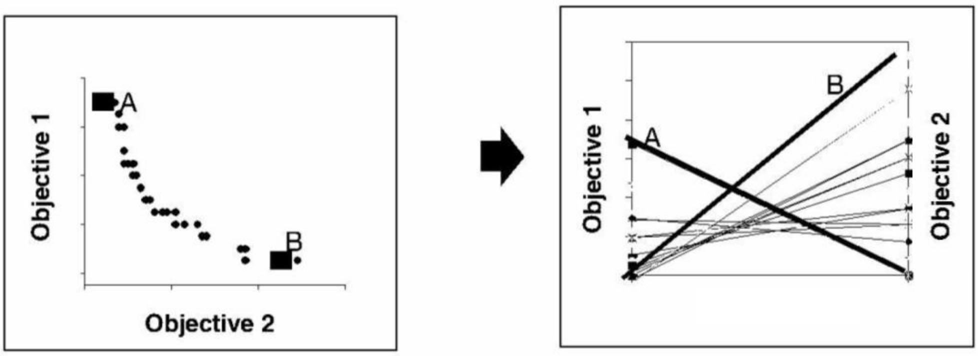


Figure 2.4 Cartesian system (left) and corresponding parallel co-ordinate (right) (source: Fleming et al., 2005)

Whilst parallel co-ordinates provide a systematic and rigorous represention of the relationship between objectives, the weaknesses of this approach are that it requires multiple views in order to capture different orderings of objectives and that it may be difficult to visualise trade-offs when there are many solutions and/or objectives that need to be considered. Nonetheless visualising trade-offs using the parallel co-ordinate approach may lead to reducing the number of objectives in the MOOP and consquently the computational effort involved in the GA's search process.

Lotov et al. (2005) developed a new approach for the visualisation of decision alternatives and applied it to a water quality planning case study for the Oka River basin in Russia. The approach was used as part of a DSS to support the screening of preferable environmental water management alternatives. The screening process was undertaken using a visualisation of these management alternatives in the form of Interactive Decision Maps (IDM). The IDM technique allows the analyst to display the feasible objective space (known as the *Edgeworth-Pareto Hull*, EPH) in the form of a Cartesian plot; two-criterion *slices* at a time (refer to Figure 2.5).

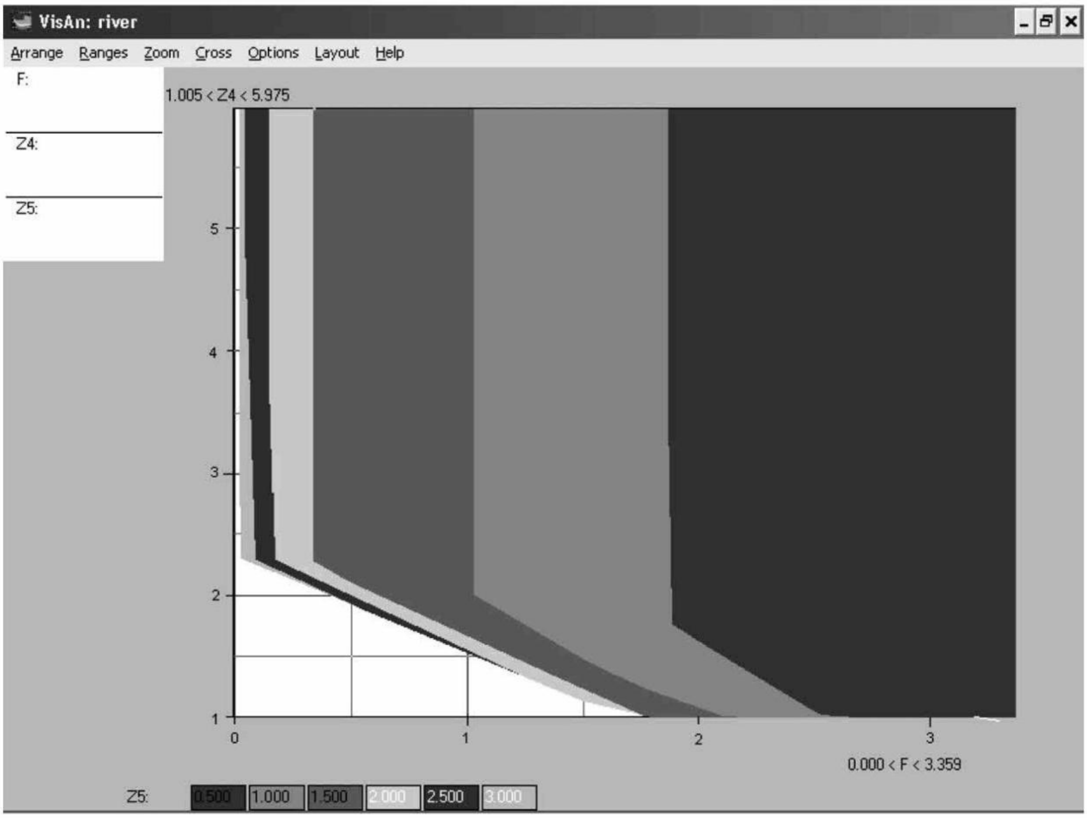


Figure 2.5 An Interactive Decision Map (IDM) (source: Lotov et al., 2005)

The analyst is able to interactively visualise different sections of the EPH much like the height contours of a topographical map. Thus, values of the third objective are similar to elevation in a topographical map. Visualisation of the fourth objective is done by selecting a given value or EPH slice for one other objective; and for visualisation of the fifth objective, values for two other objectives must be selected, and so on. Note that the analyst can animate, through the use of scroll-bars, any of these decision maps with respect to variations in any one of the objectives. Lotov et al. (2005) argued that whilst the IDM technique was capable of handling any number of objectives, they claimed that water managers would find the Pareto front too complex beyond seven objectives; potentially limiting its use.

Kollat et al. (2011) used a three-dimensional plot with a colour mapping scheme to visualise the Pareto front for a six-objective MOOP (refer to Figure 2.6). This study used a laboratory-based physical aquifer tracer experiment in order to optimise the position and frequency of tracer sampling. A total of 8,871 non-dominated solutions are shown in the plot and represented by cone-shaped markers with varying colours, orientation, and size.

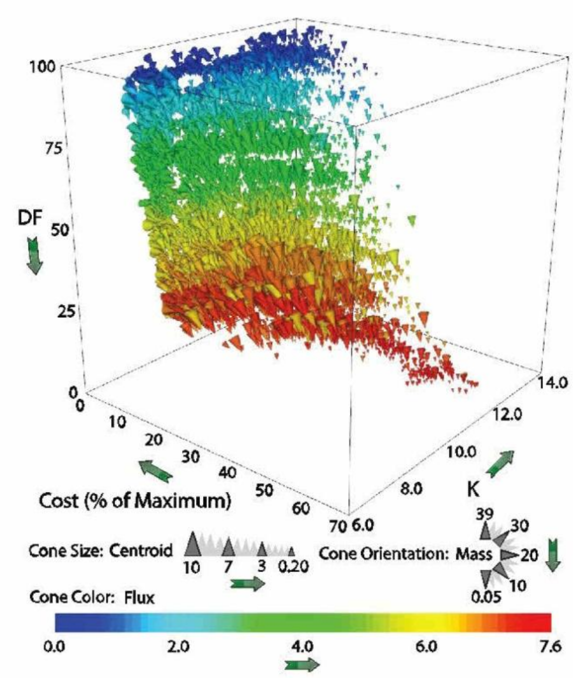


Figure 2.6 **Three-dimensional plot using cone-shaped markers with varying colours, orientation, and size (source: Kollat et al., 2011)**

With reference to Figure 2.6, the objectives of the MOOP were to (i) minimise monitoring costs (refer to “Cost” along *x*-axis); (ii) minimise detection failure (refer to “DF” along *y*-axis); (iii) maximise correction capability (refer to “K” along *z*-axis); (iv) maximise the detection of tracer fluxes (refer to “Cone Colour: Flux”); (v) minimise error in quantifying tracer mass (refer to “Cone Orientation: Mass”); (vi) and minimise the error in quantifying the centroid of the tracer plume (refer to “Cone Size: Centroid”). It is worth noting that whilst the plot is aesthetically pleasing, it may be difficult to trade off optimal solutions on Pareto fronts that have many optima.

Research has shown that as the number of objectives increases for MOOPs, so too does the dimension of the Pareto front and the proportion of non-dominated solutions to the population size (Fleming et al., 2005; Deb, 2011). For GA applications, this increase in objectives results in higher computational costs associated with the slower convergence of the population of solutions to the (higher-dimensional) Pareto front. The slow convergence is largely attributed to the dominance test which is applied to the solutions of the population, as described in Section 2.3 (refer to Equation 2.2). For example, in the case of two very similar candidate optimal solutions whose values of all but one of the many objectives are equal, the solution which has the better performing objective will dominate the other, even if that performance is minuscule. With little thought, it is easy to accept that the creation of new candidate optimal solutions will be based on solutions that are a very similar, resulting in slow progression towards the Pareto front.

Whilst the use of a large population of solutions can help overcome the issue of slow convergence, this approach may be too computationally expensive for many water resources problems; particularly for those that use intensive simulation computing effort. Note that the issue of slow convergence is not addressed in this thesis, as the main focus of this study is the novelty of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*. Notwithstanding the importance of the issue of slow convergence, an alternative to using large populations is to consider focusing the search only on that part of the Pareto front which is of interest to the DM (Fleming et al., 2005; Sinha et al., 2013). In this case, the exploitation of DM preferences may either occur *a priori*, progressively, or *a posteriori*. In *a priori* schemes, DM preferences are incorporated before the (optimisation) search begins at which time the DM may be unsure of his or her preferences. Progressive schemes allow for the incorporation of DM preferences during the search and may inform/influence the DM's preferences by information that becomes available (Sinha et al., 2013). Fleming et al. (2005) pointed out that progressive schemes are arguably the best technique for solving higher order MOOPs. In *a posteriori* schemes, the DM's preferences are applied in the selection of a preferred optimal solution(s) from the resulting Pareto front.

Sinha et al. (2013) developed a *simplify and solve* framework for solving higher order MOOPs. In the first phase, the problem was simplified by eliminating redundant objectives and in the second phase the problem was solved using a progressively interactive approach which assisted the DM in finding his or her most preferred solution. Their review of objective reduction techniques led them to employ a mixed machine learning technique for the simplification phase. For the solving phase, Sinha et al. (2013) employed the *value measurement* multi-criteria decision analysis technique which required the DM to provide the preference of one solution over another at intervals during the search process. Their justification for simplifying the problem was that it reduced the number of objectives (ideally to within the DM's congnitive capacity) and that it reduced computional effort over the course of the solving phase. However, this approach would appear to contradict the ideal multi-objective optimisation approach which firstly involves finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information (Deb, 2001).

2.3.4 Selection of most preferred optimal solution

As explained earlier in Section 2.3, planning decisions in water resources problems are characterised by multiple objectives (or criteria) and multiple interests for water. DMs are increasingly looking beyond conventional cost-benefit analysis towards more sophisticated multi-criteria decision analysis (MCDA) techniques that are able to handle a multi-objective decision environment (Bana e Costa et al., 2004). These MCDA techniques provide the basis to develop a conceptual model which represents stakeholders' preferences and value judgements (Belton and Stewart, 2002). This section describes the different classes of preference models used in MCDA problems and presents the key outcomes of some important studies which have discussed the challenges of making MCDA more accessible to real-world decision-making.

As explained by Belton and Stewart (2002), it is recognised that preference models can be classified into three broad categories, as summarised below:

- *Value measurement* models associate a real number with each solution in order to produce a preference order on the solutions, consistent with the DM's value judgements.
- *Goal*, *aspiration* or *reference level* models establish desirable or satisfactory levels of achievement for each criterion. The process then seeks to discover options which come closest to achieving these goals.
- *Outranking* models establish the strength of evidence favouring the selection of one solution over another. The process involves the pair-wise comparison of solutions in terms of each criterion.

Belton and Stewart (2002) highlighted that the aforementioned preference models contain two primary components, namely:

- a set of weights which define the relative importance or desirability of achieving different levels of performance for each criterion; and
- an aggregation scheme which allows inter-criteria comparisons or trade-offs in order to combine preferences across criteria.

In a comparison of various MCDA techniques, Hajkowicz and Higgins (2008) found strong agreement between the different techniques and concluded that the ranking of optimal solutions was unlikely to change markedly by using a different MCDA technique provided that ordinal and cardinal data were handled appropriately. Importantly, this work suggested that in many cases the major concern in the choice of MCDA technique was more to do with the ease of understanding the technique itself. They argued that this was the reason for weighted summation being the most simple and widely applied MCDA technique. In other words, DMs are more likely to use a particular MCDA technique if the results it generates are understood.

Moreover, Janssen (2001) referred to a case where MCDA was scrutinized in a court of law in the Netherlands and pointed to the greater importance of the formulation of the MOOP. The author concluded that:

> "*The main methodological challenge is not in the development of more sophisticated MCDA methods. Simple methods, such as weighted summation, perform well in most cases. More important is the support of problem definition and design*." (Janssen, 2001, p108)

The weighted summation technique transforms all criteria onto a commensurate scale (usually 0 to 1, where 1 represents the best performance) and multiplies these criteria by weights. An overall utility is the sum of the separate weighted criteria (Hajkowicz and Higgins, 2008). The selection of the most preferred optimal solution is given by the utility score closest to 1. Importantly, weighted summation does make numerous simplifying assumptions about the decision problem which if not corrected may lead to inaccurate results e.g. sometimes weighted summation produces very minor differences in utility score which may be insufficient to differentiate performance. Interestingly whilst such issues can be easily corrected, they are often overlooked in the application of weighted summation. For instance, Kularathna et al. (2011) used weighted summation as part of their decision support system without mention of a correction applied to the approach.

Loucks (1997) used weighted summation as the basis for a sustainability index which was used to describe the sustainability of water resources systems. This sustainability index combined various performance metrics to represent the reliability, resiliency, and vulnerability of water resources systems over time. Loucks (1997) demonstrated that the sustainability index could be used to evaluate water management policies and to enable the comparison of alternative policies. Moreover, in an examination of ten performance metrics undertaken by McMahon et al. (2006), the authors considered that the only quantitative measure of system sustainability which combined reliability, resiliency, and vulnerability was the sustainability index proposed by Loucks (1997). Loucks and Gladwell (1999) and Sandoval-Solis et al. (2011) further developed the concept of the sustainability index and introduced a multiplicative aggregation scheme to improve its scalability so that it did not obscure poor performance with respect to any one of its performance metrics. One of the major benefits of this sustainability index is that it can be used to summarise the performance of alternative policies from the perspective of different water users. In the context of this thesis, this attribute of the sustainability index is particularly beneficial as it can be used to explicitly account for all the major interests for water in water resources systems.

Regardless of the MCDA technique, one of the key challenges in selecting a preferred optimal solution will be to structure the MOOP consistent with the ideal multi-objective optimisation approach viz. finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information (Deb, 2001). In which case, the proposed multi-objective optimisation procedure would need to have a structure that has the capacity to incorporate all the required objective functions and the flexibility to assign weights for each objective *a posteriori.* The alternative classical multi-objective optimisation approach which combines multiple objectives into one overall single objective function would require *a priori* assignment of weights for each objective. Whilst for simple problems such classical approaches may be effective, *a priori* assignment of weights has shown to be quite ineffective and inefficient in highly non-linear, non-convex problems as mentioned in Section 2.2.4.

2.4 Summary

Chapter 2 presented a critical review of the literature on multi-objective optimisation modelling in water resources planning. The various aspects of water resources planning were presented describing the multi-criterial nature of problems concerning the operation of multi-purpose, multi-reservoir water resources systems. Multi-objective optimisation was presented as a means by which to solve such complex problems by finding new and possibly better ways to operate our systems, particularly in an uncertain climate future. Recent developments in water resources planning and multi-objective optimisation were discussed together with the associated challenges faced by researchers and decision makers (DMs) alike.

Section 2.2 described water resources planning in terms of the complex operation of water resources systems and efforts being made to incorporate sustainability principles and the latest advances in future climate projections. Whilst the review showed the positive steps that were being made with regards to incorporating sustainability principles, it highlighted the need for planning processes to take explicit account of all major interests for water and the need to incorporate the complex operating rules which control the movement of water within water resources systems.

The availability of downscaled hydro-climatic data allowed for planning processes to incorporate the latest advances in the projection of future climate and to understand which operating rules are paramount in uncertain climate future. Systems analysis techniques were presented in terms of simulation and optimisation models including the more recent optimisation-simulation (O-S) models. With respect to the challenges facing water resources planning, O-S models were described as having the essential characteristics of handling real-world water resources problems, viz.; searching for candidate optimal solutions in high-dimensional problems and simulating the behaviour of complex water resources systems.

Section 2.3 presented multi-objective optimisation as a means by which to solve water resources problems; particularly high-dimensional problems and the associated challenges of selecting a preferred optimal solution. Classical and non-classical multi-objective optimisation methods were described in terms of the ability to search for optimal solutions. Non-classical methods were described as being particularly useful for high-dimensional water resource management problems because they tended to find the entire set of Pareto-optimal solutions.

Various proof-of-concept applications of O-S models were presented highlighting the extent of applications to real-world water resources systems. A common factor to all these applications was the low number of objectives (i.e. 2-4) that were used to represent complex water resources systems. The review examined the challenges associated with the setting up of the optimisation engine and the simulation engine of an O-S model. Of interest to genetic algorithm (GA)-based O-S models, it was shown that the theory behind GAs had provided little guidance on the selection of GA operators even though these operators have a significant impact on GA performance. With respect to the setup of the simulation engine, lower-fidelity surrogate models were presented as a means to address high computational running costs and to provide the flexibility required to search for optimal solutions in high-dimensional problems.

The difficulties with solving higher order multi-objective optimisation problems (MOOPs) were described in terms of the available techniques used to visualise the Pareto front, and to address the issue of slow convergence to the Pareto front. Three visualisation techniques were examined, viz; parallel co-ordinates; Interactive Decision Maps; and a three-dimensional plot with a colour mapping scheme. Whilst these techniques had proven benefits with respect to their ability to trade off solutions, none of these demonstrated the ability to be able to easily encapsulate the visualisation of the Pareto front for high-dimensional problems.

The issue of slow convergence to the Pareto front was explained and various techniques including the use of larger population sizes were presented. It was shown that techniques which progressively incorporated DM preferences during the search for candidate optimal solutions were able to guide the search towards that part of the Pareto front which was of interest to the DM. By focusing the search in this way, the computation costs would be reduced given that only part of the Pareto front is searched. However, such techniques would appear to contradict the ideal multi-objective optimisation approach which firstly involves finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information (i.e. DM preferences).

With respect to selecting a preferred optimal solution from the Pareto front of high-dimensional problems, multi-criteria decision analysis (MCDA) techniques were presented as a means to develop a conceptual model which represented stakeholders' preferences and value judgements. The review of the literature in this area showed that the ranking of optimal solutions was unlikely to change markedly by using a different MCDA technique provided that ordinal and cardinal data were handled appropriately. This suggested that in many cases the major concern in the choice of MCDA technique was more to do with the ease of understanding the technique itself. Moreover, it was emphasised that one of the key challenges in selecting a preferred optimal solution was to structure the MOOP consistent with the ideal multi-objective optimisation approach viz. finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information (Deb, 2001). It was argued that the proposed multi-objective optimisation procedure would need to have a structure that had the capacity to incorporate all the required objective functions and the flexibility to assign weights for each objective *a posteriori.*

Chapter 3. A shared vision for the Wimmera-Glenelg Water Supply System

3.1 Introduction

This chapter describes a structured multi-objective optimisation procedure which is aimed at assisting the decision maker (DM) to develop a shared vision for the operation of complex water resource systems considering climate change. Specifically, it deals with (i) identifying all the major interests for water in a complex water resource system; (ii) the formulation of a multi-objective optimisation problem (MOOP) that takes explicit account of all the major interests for water in the system; (iii) the set up of the optimisation-simulation (O-S) model used to solve for this MOOP; and (iv) the indices used to analyse and rank optimal solutions. For this purpose, the MOOP relates to the interests for water in the Wimmera-Glenelg Water Supply System (WGWSS) with a view to developing optimal operating plans that have sustainability as an overall goal.

Chapter 1 presented a critical review of multi-objective optimisation modelling in water resources planning. It described the significance of the research and proposed a structured multi-objective optimisation procedure for the development of a shared vision for the operation of water resources systems. It also presented the aims of the study and described the research methodology. For the reader's convenience and for completeness of Chapter 3, it is important to re-state the factors related to solving higher order MOOPs which influenced the research methodology, viz; the slow convergence of solutions to the Pareto front; and the high computational costs required to progress this search. An increase in objectives has the effect of slowing the progression (i.e. *convergence*) of the population of solutions to the Pareto front. This slow convergence is largely attributed to the dominance test which is applied to the solutions of the population; resulting in a greater number of O-S modelling generations to progress the solutions towards the Pareto front. The term *generation* refers to a (single) iteration of the O-S model. An increase in the number of generations requires greater computational processing effort, which may be addressed through parallel computing processes. However, such parallel computing capabilities were not available for this thesis, which meant that simulation runs for all solutions of the population had to be completed in series (i.e. one run at a time) before the optimisation search could be executed. For these reasons (of slow convergence and high computational costs), the number of generations performed by the O-S model was limited to five in number (throughout this thesis). Importantly, this is not to be mistaken as a research limitation given that the novelty of this study is that of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*.

Chapter 2 presented a review of the literature on multi-objective optimisation modelling in water resources planning. As part of this review, it was explained that MOOPs consist of a number of objectives subject to a number of inequality and equality constraints. For the reader's convenience and for completeness of Chapter 3, the mathematical expression for a MOOP is provided again in Equation 3.1:

$$\begin{aligned} &\text{Minimise/Maximise} && f_i(x) && i = 1,2,\ldots, I \\ &\text{Subject to} && g_j(x) \leq 0 && j = 1,2,\ldots, J \\ & && h_k(x) = 0 && k = 1,2,\ldots, K \end{aligned} \qquad (3.1)$$

The parameter x is a p dimensional vector having p design or decision variables. The aim is to find a vector x that satisfies J inequality constraints, K equality constraints and minimises/maximises the I objective functions (Srinivas and Deb, 1995). Solutions to MOOPs are mathematically expressed in terms of superior or *non-dominated* points. This highlights the difficulty with MOOPs in that there is usually no single optimal solution with respect to all objectives, as improving performance for one objective means that the quality of another objective will decrease. Instead there is a set of optimal trade-offs between the conflicting objectives known as the *Pareto-optimal* solutions or the *Pareto front* (Deb, 2001). Note that whilst the term *solution* was used in Chapter 2 for the purposes of reviewing the literature, Chapters 3 to 5 use the term *operating plan* given that the focus of this study is to develop optimal operating plans for the WGWSS.

The literature review in Chapter 2 highlighted that there were many challenges that exist in the optimisation of multi-purpose water resource systems such as the need to explicitly account for a diverse range of interests for water and to develop new and possibly better ways to operate these systems under a range of hydro-climatic conditions. The review also described the positive steps that were being made with regards to the modelling of quantitative and qualitative data for integration into decision-making processes that had sustainability as a goal. Additionally, it was explained that the availability of downscaled hydro-climatic data had the potential to greatly improve water resources planning in so far as being able to include the latest advances in the projection of future climate. However, while the benefits of using O-S models were clear, it was explained that the formulation of real-world MOOPs need to take explicit account of many more interests for water than simply two or three objectives. Moreover, the increasing complexity in O-S models needs to be balanced by easy-to-understand (Pareto front) visualisation methods that allow the DM to rank and trade off optimal solutions. It was also emphasised that one of the key challenges in selecting a preferred optimal solution was to structure the MOOP consistent with the ideal multi-objective optimisation approach viz. finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information (Deb, 2001). It was argued that the proposed multi-objective optimisation procedure would need to have a structure that had the capacity to incorporate all the required objective functions and the flexibility to assign weights for each objective *a posteriori.* With all these needs in mind, it was made clear that there is a need to develop a structured procedure for the optimisation of operation of complex water resources systems considering climate change.

Of particular importance to aims (i) and (ii) described in the early part of Section 3.1, is a procedure for the formulation of MOOPs which was developed by Godoy et al. (2011), as given below:

"1. A clear statement of *stakeholders' interest for water* that form the basis of a multi-objective problem;
2. Identification of *decision variables* in the simulation model that control the operation of the system;
3. An agreed set of *objective functions* that are used to guide the search and quantify the performance of each combination of decision variables. It is recommended that the functions be based on step (1) above to ensure all stakeholders' interests are explicitly taken into account; and
4. The inclusion of real-world limits or *constraints* such as the capacity of storages, channels and pipes etc."

The authors developed this procedure specifically for MOOPs that related to complex water resource systems and which were to be solved using an O-S model. This procedure was used as a starting point for the formulation of the MOOP presented in this thesis.

The WGWSS is a large-scale, multi-storage system that is regulated using a set of complex operating rules to meet the needs of a variety of water-based uses. Each water user group has its own individual needs and interests for water which are often conflicting and non-commensurate with those of other user groups. For instance, water that is passed at storages and diversion structures for environmental purposes is often in direct conflict with that water which would have otherwise been diverted for consumptive purposes. Moreover, the consequences of a shortfall in supply to one user may not have the same severity as that for another user, particularly during water shortages when the essential needs of users become a focus. The interests for water in the WGWSS are broadly categorised and presented in terms of those that are environmental, social (i.e. recreation, cultural, and water quality purposes), consumptive, and those that affect all users system-wide. These interests for water are represented in a simulation model (referred to as “the Wimmera-Glenelg REALM model”) together with the key operating rules which are used to control and regulate the water resources within the WGWSS. REALM is a structured computer software package that simulates the harvesting and bulk distribution of water resources within a water supply system (Perera et al., 2005). For the purposes of evaluating and comparing the performance of these modelled operating rules (referred to as “operating plans”), three performance metrics (viz. reliability, resiliency, and vulnerability) are presented and discussed. Refer to Section 3.2 for details of this part of the study.

Having identified all the major interests for water in the WGWSS, a higher order MOOP is formulated with sustainability as an overall goal. A higher order MOOP is defined in this thesis as a problem that is formulated with more than three objective functions. The problem is structured hierarchically; the sustainability of the WGWSS is assumed to represent the highest level criteria, followed by the four major interests for water (i.e. environmental, social, consumptive, and system-wide), and with the lowest level criteria representing the 18 objective functions for the MOOP. The decision variables are expressed in terms of 24 water management planning decisions representing the key operating rules which are used to control and regulate the water resources within the WGWSS. The planning decisions are categorised into six areas of system operation viz. (i) *priorities of supply* between different sources of supply and between different user groups; (ii) a *storage flood reserve volume* to provide flood attenuation; (iii) *environmental allocation shares* for apportioning environmental water allocations between river basins; (iv) the preference of alternative *flow paths* for the harvesting and/or transfer of water; (v) *storage maximum operating volumes* for the key water harvesting storages; and (vi) *storage draw down priorities and storage targets*. The mathematical equations for the 24 decision variables are presented and reference is made to the relevant carriers and storages contained in the Wimmera-Glenelg REALM model. The real-world limitations of the WGWSS are also presented in the MOOP in terms of bounds on variables, integer constraints, statutory constraints, and physical constraints. Refer to Section 3.3 for details of this part of the study.

The O-S model that is used to solve the higher order MOOP is presented in terms of the optimisation engine and the simulation engine. The setup of the optimisation engine was aimed at demonstrating the novelty of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*. To that end, the optimisation engine was set up to find the best non-dominated operating plans for evaluation using the indices described later in Section 3.1. The optimisation engine comprises the Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) and the simulation engine is the REALM software package. The process is iterative; simulation outputs are used to calculate the 18 objective functions which are in turn passed to the optimisation engine. The optimisation engine continues to iterate to a candidate optimal operating plan until convergence has been achieved or some stopping criterion has been reached. Note that many researchers describe this iterative process as one of *searching* or *finding* a candidate optimal solution. The genetic operators (i.e. selection, crossover, and mutation) of the NSGA-II are described together with the optimisation parameters adopted for the higher order MOOP. The set up of REALM is presented in terms of the Wimmera-Glenelg REALM model and the input data files for the hydro-climatic data and water demands. For the purposes of this thesis, three hydro-climatic scenarios are presented representing historic conditions (over the period 1891 to 2009) and two greenhouse gas (GHG) emission scenarios. The two GHG emission scenarios represent the lower and higher ends of the estimated range of GHG emissions as given by the Intergovernmental Panel on Climate Change or IPCC (IPCC, 2000). The motivation for choosing these bookend estimates is that the search for candidate optimal operating plans would be undertaken over the widest plausible range of future hydro-climatic conditions. The “low to medium level” and “medium to high level” GHG emission scenarios selected are estimated to result in total cumulative global carbon dioxide emissions ranging from approximately 800 GtC to 1,400 GtC and 1,400 GtC to 2,000 GtC by 2100 respectively (IPCC, 2000). The units GtC means gigatonnes of carbon. Refer to Section 3.4 for details of this part of the study.

The indices used to analyse and rank optimal operating plans are developed from the hierarchical structure of the higher order MOOP (described earlier). The highest level represents the Sustainability Index (SI) which is used to evaluate optimal operating plans with respect to all the major interests for water in the WGWSS. The second level of the SI is expressed in terms of a Component-level Index for the i^{th} interest for water (CI_i) viz. (CI_{env}) for the environmental interests, (CI_{socio}) for the social interests, (CI_{cons}) for the consumptive interests and (CI_{sys}) for the system-wide interests for water. The lowest level of the SI features the 18 performance metrics (described earlier). These lowest level indicators (referred to as “the sub-indicators”) are particularly important in terms of providing the link between the interests for water in the WGWSS and the search for candidate optimal operating plans. Thus, the search for candidate optimal operating plans is relevant to the problem at hand; a desire to develop optimal operating plans for the WGWSS that have sustainability as an overall goal. Moreover, the SI can be adapted to include stakeholders’ preferences so that it can be used as part of the process of ranking optimal operating plans. The process of ranking optimal operating plans brings together two aspects of multi-objective optimisation, namely; (i) the quantitative information regarding the characteristics of the optimal operating plans along the Pareto front; and (ii) the higher level qualitative information in the form of stakeholders’ preferences. For the purposes of this selection process, the j^{th} stakeholder’s Weighted Sustainability Index (SI^j) and Weighted Component-level Index (CI_i^j) is presented and discussed. Refer to Section 3.5 for details of this part of the study.

3.2 The Wimmera-Glenelg Water Supply System

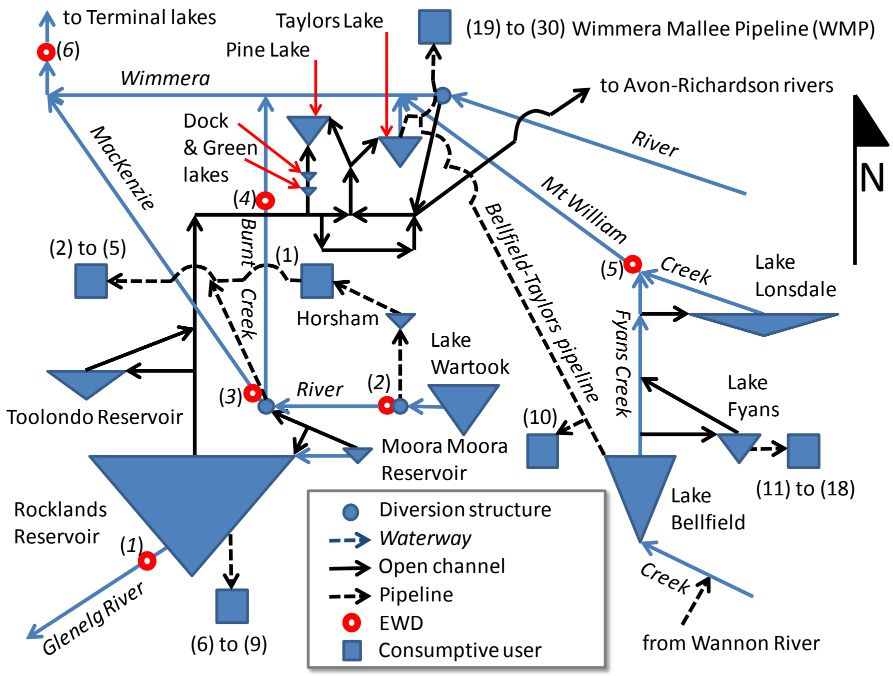
3.2.1 The study area

The WGWSS is located in north-western Victoria (Australia) and is a large-scale, multi-storage system operated by Grampians Wimmera Mallee Water Corporation

(GWMWater). The WGWSS covers an area of approximately 62,000 km^2 and is divided into seven major supply areas referred to as "Supply Systems" (see Figure 3.1).

Figure 3.1 The WGWSS showing Supply Systems 1 to 7

Supply System 5 is supplied exclusively from the Murray River and is not affected by the operating rules that control the headworks of the WGWSS. As the focus of this thesis relates to the operating rules for the headworks, the study area is defined as Supply Systems 1, 2, 3, 4, 6, and 7. Note that for convenience, the study area is referred to as the WGWSS throughout this thesis as it includes most of the Supply Systems. Figure 3.2 is a schematic of the WGWSS showing the Wimmera and Glenelg river systems, the 12 headworks storages that are used to harvest these streamflows, and the network of open channels and pipelines used to transfer water between the storages and to meet the needs of a variety of water-based uses.



Note: Numbers in brackets refer to environmental water demands or EWDs (italic font) and consumptive water demands (regular font) configured in the Wimmera-Glenelg REALM model (refer to Section 3.2.2).

Figure 3.2 Schematic of the Wimmera-Glenelg Water Supply System (not to scale)

Specifically, the system comprises:

- 10 storages that source water from the Wimmera River catchment either as direct inflows or through transfers via channel systems within the headworks;
- 2 storages and 2 diversion weirs that source water directly from the Glenelg River catchments either as direct inflows or through transfers via channel systems;
- Huddleston's weir that diverts water from the Wimmera River into the Wimmera Inlet Channel;

- Dad and Dave weir that diverts water from the MacKenzie River into Mt Zero Channel for supply to Horsham;
- A network of open channels and pipelines that transfer water between storages; and
- the Wimmera Mallee Pipeline which distributes water from the headworks to Supply Systems 1, 2, 3, and 4 for watering of stock and for domestic, urban and industrial consumption.

The headworks storages (summarised in Table 3.1) and the extensive distribution network are operated as a single water resource system (with many possible combinations of operating rules) to meet the needs of a variety of water-based uses.

Table 3.1 Headworks storages in the WGWSS (as in Wimmera-Glenelg REALM model)

River basin	**Headworks storages**	**Full Supply Volume** (ML)	**Full supply level to Australian height datum** (metres)
Wimmera	Lake Bellfield	76,000	276.50
	Lake Fyans	18,460	203.79
	Lake Lonsdale	65,000	187.62
	Taylors Lake	33,700	144.61
	Lake Wartook	29,360	441.69
	Horsham storages	328	310.10
	Toolondo Reservoir	92,430	164.91
	Dock Lake*	5,900	134.02
	Green Lake*	5,350	135.70
	Pine Lake*	64,200	143.89
Glenelg	Moora Moora Reservoir	6,300	219.95
	Rocklands Reservoir	348,000	195.47

* These storages are not for water supply purposes

Note that whilst Dock Lake, Green Lake, and Pine Lake are not operated for supply of water to entitlement holders, these storages continue to be operated for other uses such as for recreation and for flood mitigation purposes.

3.2.2 The Wimmera-Glenelg REALM model

The origins of the simulation model developed for this thesis begin with a REALM model provided by the Department of Environment, Land, Water and Planning (DELWP) in 2010 (pers. comm. Michael Finger). The DELWP identified this model, or *system file* as it is referred to in REALM, as the "WMPP2104.sys file." Over the last 20 years of its development, the WMPP2104.sys file (and its predecessors) have been used in numerous simulation modelling studies largely for the purposes of supporting strategic long term planning processes (Godoy Consulting, 2014). In recent times, this high quality simulation model was endorsed by the Murray-Darling Basin Authority as part of its model accreditation process under the Murray-Darling Basin Plan (MDBA, 2011). More recently a review of the operation of the WGWSS was undertaken using the simulation model to test the effectiveness of the current operating rules against stakeholders' storage management objectives (GWMWater, 2014). It is worth highlighting that researchers generally agree that the use of trusted simulation models would have the potential of giving stakeholders and DMs greater confidence in O-S modelling results (Maier et al., 2014).

As part of the process of setting up the O-S model (which is described in Section 3.4), it was discovered that modifications to the WMPP2104.sys file were required in order for it to connect to the optimisation engine and to improve its capability of searching for candidate optimal operating plans. For this purpose, a *lower-fidelity physically based surrogate model* was developed based on the original simulation model (i.e. the WMPP2104.sys file). This surrogate model is referred to as the "Wimmera-Glenelg REALM model" in this thesis. Razavi et al. (2012) described this type of surrogate model as one that is (physically) based on the original simulation model preserving the main functionality; but is less detailed. Refer to Section 3.4.1.1 for further details regarding the benefits of using a lower-fidelity physically based surrogate model in higher order MOOPs. Figure 3.3 shows the Wimmera-Glenelg REALM model as seen through the graphical editor window in the REALM software package. This graphical representation is very similar to the schematic of the WGWSS shown in Figure 3.2, albeit with much greater detail. For the reader's convenience, the headworks storages of the WGWSS are noted in Figure 3.3.

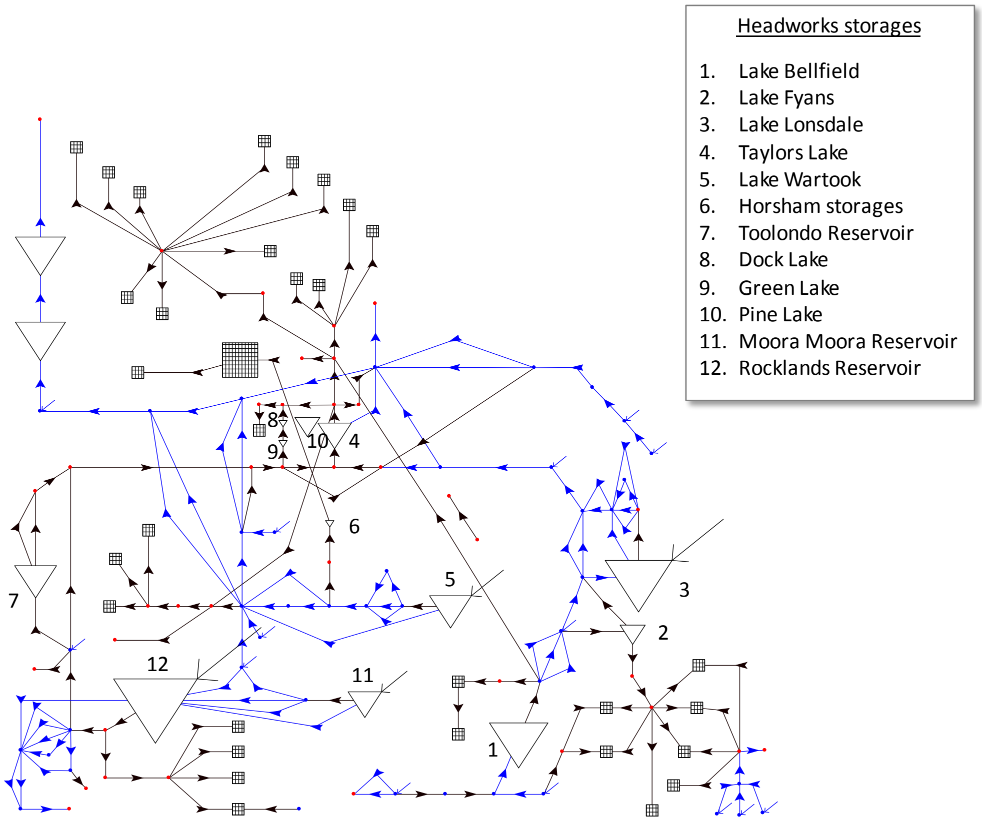


Figure 3.3 The Wimmera-Glenelg REALM model

The Wimmera-Glenelg REALM model together with the input data representing streamflows, rainfall, evaporation, and water demands are collectively referred to as a model "scenario" or "run" in this thesis. In addition to the model containing the physical representation of the WGWSS, it also includes all the key operating rules that regulate water throughout the system. These modelled operating rules are collectively referred to as an "operating plan" in this thesis. The operating plan embedded in the WMPP2104.sys file represents the current practice in the WGWSS. This operating plan was configured in the Wimmera-Glenelg REALM model and is referred to as the "base case operating plan" and the model run is referred to as the "base case scenario" throughout this thesis. It is important to highlight that the base case scenario is a simulation-only run and that it is used for the purposes of providing a point of reference in the analysis of the optimal operating plans found by the O-S model. For this purpose, the base case scenario is run using one of the following hydro-climatic conditions which are more fully described in Section 3.4.1.2.1:

- historic hydro-climatic conditions;
- low to medium level GHG emissions; or
- medium to high level GHG emissions.

With exception of the hydro-climatic input data above, all the modelling scenarios presented in this thesis (i.e. the base case scenarios and the O-S scenarios) have the same model specifications as follows:

- a choice of two planning periods, viz. January 1891 to June 2009 for historic hydro-climatic runs or January 2000 to December 2099 for future GHG emissions;
- monthly time-step;
- environmental demands representing passing flow rules and prioritised water flow requirements (refer to Section 3.2.3.1); and
- consumptive demands representing full utilisation of water entitlements (refer to Section 3.2.3.3).

Note that unlike the environmental and consumptive demands which are specified in separate input data files, the interests for water in the WGWSS that have a social focus (e.g. recreation) and those that affect all water users system-wide (e.g. water allocations) are embedded in the operating rules of the Wimmera-Glenelg REALM model. The reasons for this setup are explained in Section 3.2.3.2.

3.2.3 Stakeholders' interests for water

Belton and Stewart (2002) describe multi-criteria decision making in water resource planning studies as "mixed design and evaluation problems." The authors explain that such problems typically involve many stakeholders who are required to make in-depth value judgements in relation to alternatives presented to them and that in practice these comparative evaluations can only be performed on a relatively small number of discrete options given the human cognitive load. In the context of this thesis, the "design" stage generates a suitable shortlist of optimal operating plans for a detailed "evaluation" by the DM.

It is worth highlighting that for this thesis, there is a distinction made between those whom have an interest for water and provide value judgements (i.e. stakeholders), and those that have the ultimate decision-making power under law (e.g. DM). Based on a recent Government-led planning study in the WGWSS, the key stakeholders were water entitlement holders (i.e. water corporations and the Victorian Environmental Water Holder) and the catchment management authorities (DSE, 2011). In that study, the DM was the Minister for Environment, Climate Change and Water ("the Minister"). With respect to those planning studies led by water corporations and the Victorian Environmental Water Holder, the key stakeholders are often community members that encompass a wide range of interests and the DM is the water corporation or VEWH (GWMWater, 2012a; 2012b; 2007; 2014; VEWH, 2013). However, in some of these latter studies, the water corporation is in a sense a stakeholder advocate that uses the value judgements of its customers to formulate its own institutional values in a submission to the Minister (GWMWater, 2007; 2014). Importantly for this thesis, it is assumed that the stakeholders and the DM are as per DSE (2011); the stakeholders are the water entitlement holders and the catchment management authorities, and the DM is the Minister. It is also worth pointing out that the above studies involved the use of (REALM) simulation modelling outputs to support multi-criteria decision making processes.

For the purposes of this thesis, the data collected as part of the above planning studies in the WGWSS has been used in a desktop study to (i) identify stakeholders' interests for water in the WGWSS together with any relevant criteria by which to evaluate candidate optimal operating plans; (ii) identify any relevant water management planning decisions as part of the formulation of the MOOP; and (iii) postulate stakeholders' judgement values in relation to the selection of a preferred optimal operating plan from a Pareto front (refer to Section 5.3).

As part of this desktop study, the various interests for water identified in the WGWSS have been categorised into four major groups i.e. environmental, social, consumptive, and those that affect all users system-wide. In recognition of the importance of properly identifying interests and values in the water planning decision-making process (Mooney et al., 2012), these four major interests for water are presented in Sections 3.2.3.1 to 3.2.3.4 and serve as the basis of the conflicting objectives of the higher order MOOP for the WGWSS.

3.2.3.1 Environmental

The environmental water within the WGWSS is held in trust by the Victorian Environmental Water Holder and the Commonwealth Environmental Water Holder (VEWH, 2014):

The Victorian Environmental Water Holder's environmental water holding consists of:

- 41,560 ML/year of high reliability regulated water available from any storage within the headworks system subject to water availability in the WGWSS;
- passing flows of a lower reliability at five locations including the Glenelg River at Rocklands Reservoir, Wimmera River at Huddlestons Weir, Mt William Creek at Lake Lonsdale, Fyans Creek at Stawell Diversions Weir and the Wannon River at Wannon Diversion; and
- storage spills and any other catchment inflow that is not harvested by the headworks system and extracted by private diversions.

The Commonwealth Environmental Water Holder's environmental water holding consists of 28,000 ML/year of high reliability regulated water subject to water availability in the WGWSS. This entitlement originates from the sale of GWMWater's irrigation water which became effective in the 2014-15 water year (VEWH, 2014). Note that the Wimmera-Glenelg REALM model assumes that the 28,000 ML/year is available to the environment as a low reliability allocation – refer to Section 3.2.3.4 for further details.

The Victorian Environmental Water Holder (VEWH) performs this role in consultation with waterway managers which in this case are the Glenelg-Hopkins and Wimmera catchment management authorities. The waterway managers play the key role of engaging with land managers, the storage operator (i.e. GWMWater), local landholders and the community in the development of seasonal watering plans. The VEWH also co-ordinates its efforts with other Australian jurisdictions including the Commonwealth Environmental Water Holder (CEWH) and partners in the Living Murray Program. The VEWH reports to the Minister and the DELWP has a role in advising the Minister of the VEWH's performance in meeting its objectives and functions as set out in Sections 33DA-33DZA of the *Water Act 1989* (Vic).

The *Seasonal Watering Plan 2014-15* sets out the environmental watering program for all major river systems in Victoria including the Wimmera and Glenelg rivers (VEWH, 2014). With reference to the numbering scheme adopted in Figure 3.2, the following is a summary of the key environmental assets for each of the six stream reaches configured in the Wimmera-Glenelg REALM model:

1. Glenelg River – this reach is home to a number of important native fish populations including river blackfish and a number of galaxid and pygmy perch species. This reach also supports good riparian vegetation, including the newly-discovered, endangered Wimmera bottlebrush (VEWH, 2014);

2. MacKenzie River (upper) – this is the only reach in the Wimmera basin that contains populations of platypus and all endemic fish species (VEWH, 2014);

3. MacKenzie River (lower) – this is the only reach in the Wimmera basin that contains populations of the endangered Wimmera bottlebrush (VEWH, 2014);

4. Burnt Creek – there have been river blackfish recorded in great abundance in this reach and the riparian zone is characterised by a River Red Gum over-storey (Alluvium, 2013b);

5. Mt William Creek – this reach contains a large assemblage of native species including Mountain Galaxias and the vulnerable Southern Pygmy Perch. The riparian vegetation is in reasonable to good condition particularly in the upper section where it borders the Grampians National Park (Alluvium, 2013b); and

6. Wimmera River – most of this reach has been declared a heritage river under the *Heritage Rivers Act 1992* (Vic) for its biological, cultural and recreational values, particularly in association with the terminal lakes. Additionally, the weir pools at Dimboola and Jeparit are of high social and recreational significance. Lake Hindmarsh is the largest freshwater lake in Victoria and supports a number of environmentally significant values, including River Red Gum and Black Box communities. Lake Albacutya which is approximately 15 km downstream of Lake Hindmarsh is a Ramsar listed wetland of international conservation significance. It fills only intermittently when Lake Hindmarsh overflows. Both lakes support about 50 species of waterbird including the endangered Great Egret and Freckled Duck. This reach contains other important values including populations of freshwater catfish and endemic fish such as the Flathead Gudgeon and Australian Smelt and a stocked population of introduced, but vulnerable Golden Perch, Silver Perch and Freshwater

Catfish. The upper section of this reach borders Little Desert National Park, where the uncleared bushland supports a floodplain and riparian zone in excellent condition (Alluvium, 2013b).

The environmental flow requirements of the above stream reaches were quantified as part of a freshwater ecological study (Alluvium, 2013a; 2013b). These flow requirements are configured in the Wimmera-Glenelg REALM model as separate environmental water demands (EWDs) in order to provide for the required flows (refer to Figure 3.2). Unregulated or run-of-river flows are used in the first instance to meet EWDs followed by regulated flows if there is any residual demand (GHD, 2011). In this case, a criterion that could be used to evaluate candidate optimal operating plans with respect to EWDs, would be the difference between the amount that is required at a particular location (i.e. demand) and the amount that is provided to that location (i.e. supply). This difference in the demand and supply at any given location is referred to as a "flow deficit" in this thesis, or "environmental flow deficit" to be precise. Such criteria together with the performance metrics in Section 3.2.4 are incorporated in the formulation of the higher order MOOP by way of objective functions, f_1 to f_3 (refer to Section 3.3.1).

3.2.3.2 Social

3.2.3.2.1 Recreation

Social interests for water in terms of recreation are significant in the WGWSS and vary widely. For instance, boating and skiing enthusiasts require a safe minimum water level to ensure that they do not hit underwater obstacles (e.g. tree stumps), while others prefer to have a wide sandy berm for sand play by young children. In fact water-based recreational activities are so plentiful in the WGWSS that industries have emerged to cater for the large number of visitors to such activities. These tourism enterprises are important in the WGWSS for socio-economic reasons, contributing to the economy and generating employment. This section focuses on the recreation amenity provided at Lake Lonsdale and Lake Fyans based on two recent planning studies undertaken by GWMWater (2012a; 2012b).

GWMWater (2012a) points out that the primary role of Lake Lonsdale is as a source of environmental water for the WGWSS, and that providing for recreation amenity at the storage is a secondary goal. Recreational activities at Lake Lonsdale include picnicking, walking, camping, fishing, canoeing, swimming, boating, skiing and sailing. GWMWater (2012a) states that it was estimated that the contribution of Lake Lonsdale to the local and regional economy was about $1.6 million annually in direct and indirect benefits based on indicative visitor numbers. According to GWMWater (2012a), the minimum desirable level beyond which recreation amenity is much reduced is at 1.5 metres or 5,379 ML in storage.

Lake Fyans is used by those living in Stawell, Ararat and the wider western district for a range of water based recreation including fishing, swimming, powered and non powered boating and sailing, water skiing, bird watching, duck shooting, and non-water based pursuits such as bush walking and bike riding. GWMWater (2012b) states that the fishing scouting, sailing, water skiing, swimming and holiday park patronage directly contributed in excess of $7.8 million to the local economy in 2011. It estimated that the employment generated by that economic input was about 95 full-time equivalent jobs and that this contributed to more than $23.3 million annually. According to GWMWater (2012b), a suitable minimum water level for recreation is 1.5 metres or 1,761 ML in storage.

Moreover, one lobby group has focused on the importance of recreation in terms of the social well-being of communities in the WGWSS (The Wimmera Mail-Times, 2013b; 2013c). The Natimuk Lake Action Group asserts that the recent review of the operation of the WGWSS by GWMWater (2014) did not adequately address recreation interests because it did not consider the mental and physical health of people in the WGWSS, particularly the younger generation whom it claims did not have many healthy recreation options at that time.

GWMWater holds an entitlement for recreation of 2,590 ML/year subject to water availability in the WGWSS. Whilst this represents a small proportion of the total entitlement volume in the WGWSS (i.e. $\frac{2,590}{97,550} = 2.7\%$), recreation amenity is also provided by water held in storage. GWMWater (2012) explains that the operator has limited discretion to move water around the WGWSS for meeting recreation needs only. Instead, the operator provides different types of recreation amenity by changing certain operating rules within the operating plan. In this case, a criterion that would be used to evaluate candidate optimal operating plans with respect to recreation at Lake Lonsdale and Lake Fyans is the volume held in those storages. Such criteria together with the performance metrics in Section 3.2.4 are incorporated in the formulation of the higher order MOOP by way of objective functions, f_4 to f_9 (refer to Section 3.3.1).

3.2.3.2.2 Cultural

As for the recreation-based social interests for water described in Section 3.2.3.2.1, this section focuses on the cultural values that exist at Lake Lonsdale and Lake Fyans based on the same planning studies undertaken by GWMWater (2012a; 2012b). Lake Lonsdale and Lake Fyans have been mapped as an area of cultural heritage sensitivity under the *Aboriginal Heritage Act 2006* (Vic). The two Traditional Owner Groups in the region are the Gunditj Mirring and the Barengi Gadjin Land Council.

According to Emsconsultants (2009), little is known of the cultural values associated with the Lake Fyans storage area given that it has not been surveyed for aboriginal occupation. However, as Lake Lonsdale has been surveyed for aboriginal occupation, more is known of the cultural connection it has with indigenous people. For instance, when Lake Lonsdale is not empty it has been documented that it protects a number of burial sites on the storage bed. The largest of these archaeological deposits occurs across the north eastern part of the storage. Moreover, a study undertaken by Emsconsultants (2009) as part of the Western Region Sustainable Water Strategy (DSE, 2011) reveals that indigenous people are critical of non-indigenous water resource management. This is mainly due to indigenous people having a different view on water and a belief that it is inextricably related to the land, playing a significant role in traditional and cultural practice. According to Emsconsultants (2009), indigenous people observed burial sites being damaged during the period 1997 to 2010 by cars being driven across the dry (Lake Lonsdale) storage bed and by farmers grazing their stock over it. Another criticism highlighted by Emsconsultants (2009), is that indigenous people were not consulted in the Victorian Government's conversion of rights to water to bulk water entitlements in the WGWSS.

Emsconsultants (2009) lists the following sites within the WGWSS as having cultural significance:

- all waterfalls and underground water in the Grampians National Park which indigenous people refer to as *Gariwerd.* (Note that the WGWSS headworks are located in and around the Grampians National Park);
- Yarriambiack Creek (a tributary of the Wimmera River);

- all wetlands of the upper Glenelg River (upstream of Rocklands Reservoir);
- the many waterways in the region which have the highest concentration of scar trees in Australia;
- Toolondo Creek (a stream which runs into Toolondo Reservoir); and
- McKenzie Creek.

The criterion that would be used to evaluate candidate optimal operating plans with respect to cultural values at Lake Lonsdale is the volume held in storage. However, as the desired recreation amenity at Lake Lonsdale requires a volume that is greater than that for cultural purposes, the criterion for recreation interests for water described in Section 3.2.3.2.1 will also suffice for cultural purposes. Similarly, it is anticipated that the provision for recreation amenity at Lake Fyans would go some way to protect the cultural heritage associated with that storage area.

3.2.3.2.3 Water quality

As operator of the WGWSS, GWMWater is responsible for operating the WGWSS to supply entitlement holders with water that is fit for purpose. It does this by operating to a set of water quality targets for each storage (e.g. salinity, turbidity etc) with due consideration to any exceptional circumstances (e.g. bushfire, flooding etc). However as the Wimmera-Glenelg REALM model is not setup to account for such water quality parameters, this thesis focuses on the (storage) operation of the WGWSS in so far as managing water quality is concerned. Whilst all storages in the WGWSS have operating rules associated with maintenance of water quality, Rocklands Reservoir is presented given that it is the largest and arguably the most important storage in the system.

In addition to Rocklands Reservoir being an important source of water to the Glenelg River, it also supports the entire system by holding the majority portion of carryover water, reserve for following year, and water to consumptive users. During times when Rocklands Reservoir is relatively low the salt level becomes elevated. Historically, it has been observed that dry periods can have the effect of accumulating salt and nutrients and that high inflows can result in high levels of colour. This is of particular concern to a consumptive user (i.e. Wannon Water – refer to Section 3.2.3.3) which is dependent on Rocklands Reservoir; requiring water from Rocklands Reservoir to be mixed with water sourced from its local diversions (which are often of better quality) in order to achieve an acceptable salt level. According to GWMWater (2011), the strategy for maintaining water quality within Rocklands Reservoir is: (i) the continued turn-over of large volumes of water which coincides with the delivery of environmental passing flows as inflows occur; and (ii) a minimum desirable level of 189.06 m Australian Height Datum (AHD) or 69,600 ML in storage. This minimum operating level assists to manage water quality, particularly salinity levels, by buffering poor quality inflows during low inflow years. Additionally, this minimum operating level provides some recreation amenity (GWMWater, 2011).

In this case, the criterion that would be used to evaluate candidate optimal operating plans with respect to the management of water quality at Rocklands Reservoir is the volume held in storage. Such criteria together with the performance metrics in Section 3.2.4 are incorporated in the formulation of the higher order MOOP by way of objective functions, f_{10} to f_{12} (refer to Section 3.3.1).

3.2.3.3 Consumptive

Consumptive use in the WGWSS is managed by GWMWater, Wannon Water and Coliban Water. These government-owned water corporations are established under Section 85 of the *Water Act 1989* (Vic) and must provide, manage, operate and protect water supply and sewerage systems for urban customers including collection, storage, treatment, transfer and distribution functions as required. In addition to operating the WGWSS, GWMWater holds an entitlement for 81,570 ML/year and supplies water to approximately 52,000 urban properties in 71 towns and 11,000 rural customers, provides wastewater services to 26 towns, and supplies reclaimed water to 39 end users (GWMWater, 2012c). Wannon Water holds an entitlement of 2,120 ML/year and sources its water directly from Rocklands Reservoir to supply Balmoral and to supplement supplies to the townships of Hamilton and Cavendish located in the Glenelg Basin (Wannon Water, 2012). Coliban Water holds an entitlement of 300 ML/year and sources its water directly from the Wimmera Mallee Pipeline (WMP) to supply a residential population of 986 located in Wedderburn, Korong Vale, Borung and Wychitella (Coliban Water, 2012). All three water corporations hold entitlements of high reliability water, subject to water availability in the WGWSS.

All water corporations in Victoria (Australia) are required to prepare a Water Supply Demand Strategy (WSDS) which sets out a 50-year strategy to balance the supply of water to meet residential, business and community water needs (DSE, 2011). WSDSs are reviewed every five years and are a key input into every corporation's strategic planning process. WSDSs set out a corporation's long term level of service objectives which may be considered in the context of this thesis, as consumptive user criteria. Whilst these service objectives are system-specific, characterised by a particular system's supply and demand needs, there are common criteria employed to evaluate candidate optimal operating plans with respect to supply consumptive demands as follows:

- *Reliability of supply* – a term used to indicate the frequency of restrictions. Reliability is often expressed as the probability of years that water restrictions will not be imposed (Erlanger and Neal, 2005). In this case, GWMWater and the other two water corporations (i.e. Wannon Water and Coliban Water) have agreed to provide urban customers with their respective unrestricted demand in 93% and 95% of years respectively, assuming historic hydro-climatic conditions (GWMWater, 2012c; Wannon Water, 2012; Coliban Water, 2012).
- *Maximum restriction level* – a term used to indicate the severity/duration of restrictions. Wannon Water and Coliban Water have agreed to provide no worse than stage 3 (out of 4) level of restrictions (but do not specify any maximum duration of restriction (Wannon Water, 2012; Coliban Water, 2012). GWMWater sets a *minimum level of service* in which it agrees to supply at least 50% of the unrestricted demand in years where restrictions are in force (GWMWater, 2012c).

The Wimmera-Glenelg REALM model includes 30 separate consumptive demands for reasons of accounting for water corporations' demand type and source of supply (refer to consumptive user (1) to (30) in Figure 3.2). Similar to the criterion for the environment described in Section 3.2.3.1, a criterion that could be used to evaluate candidate optimal operating plans with respect to consumptive demands, would be the difference between the demand at a particular location and the amount supplied to that location. This difference in the demand and supply at any given location is referred as "consumptive user deficit" in this thesis. Such criteria together with the performance metrics in Section 3.2.4 are incorporated in the formulation of the higher order MOOP by way of objective functions, f_{13} to f_{15} (refer to Section 3.3.1).

3.2.3.4 System-wide

An interest for water that was raised by most stakeholders was the water allocations in the WGWSS, specifically the "reliability" of full water allocations. The reason for this is due to the fact that the supply to all water users is affected by these water allocations. The Wimmera-Glenelg bulk water entitlements specify each entitlement holders' share of the resource (or water allocation) subject to the available water in the WGWSS (VGG, 2010). The available water in the WGWSS is defined as the total volume of water available for allocation to all entitlement holders. Table 3.2 shows that at any given volume of "Water Available", an entitlement holder has a pre-defined (volumetric) share of that volume of water.

Table 3.2 Shares of Water Available (source: VGG, 2010)

WATER AVAILABLE (ML)	A	B	C	D	E	F
	125,550	97,550	75,971	53,459	45,253	0
Grampians Wimmera Mallee Water						
System operating water:						
Irrigation losses	9,000	0	0	0	0	0
Pipeline and balancing storage losses	2,960	2,960	2,960	2,960	2,960	0
Irrigation product	19,000	0	0	0	0	0
Glenelg compensation flow	3,300	3,300	825	50	50	0
Recreation	2,590	2,590	648	0	0	0
Wimmera-Mallee Pipeline product	44,720	44,720	36,352	25,725	21,540	0
Coliban Water						
Wimmera-Mallee Pipeline product	300	300	244	173	145	0
Wannon Water						
Wimmera-Mallee Pipeline product	2,120	2,120	1,723	1,220	1,021	0
Environment						
Wetlands	1,000	1,000	250	0	0	0
Wimmera-Mallee Pipeline product	40,560	40,560	32,970	23,332	19,537	0

Notes

1. All numbers in the table are in ML.
2. If the volume of water available is greater than shown for column A, the share is equal to the volume shown in column A.
3. If the volume of water available is between any two columns, the share is linearly interpolated between the shares in the adjacent columns.
   For example, if there is 60,000 ML of water available (between columns C and D), Wannon Water's share is equal to:
   [(1,723-1,220)x(60,000-53,459)/(75,971-53,459)]+1,220 = 1,366 ML
4. The calculation in Note 3 is to be rounded to the nearest whole number.

Table 3.3 provides the method for estimating the Water Available in the WGWSS. The above shares of Water Available (Table 3.2) and calculation of Water Available (Table 3.3) are configured in the Wimmera-Glenelg REALM model. It is important to note the following model assumptions with regards to these computations which are consistent with DELWP's REALM model, WMPP2104.sys (refer to Section 3.2.2):

- Grampians Wimmera Mallee Water's (i.e. GWMWater's) 28,000 ML irrigation allocation (i.e. 9,000 ML "irrigation losses" plus 19,000 ML "irrigation product") is available to the environment as a low reliability allocation in recognition of the water entitlement purchased by the environment. Therefore, the total system water allocation in column A of Table 3.2 is 97,550 ML (i.e. 125,550 ML less 28,000 ML).
- The *measured total volume in store at the start of month i* is the sum of the modelled volume held in Rocklands Reservoir, Taylors Lake, Toolondo Reservoir, Lake Bellfield, Moora Moora Reservoir, Lake Lonsdale, Lake Wartook, and Lake Fyans. "Month i" refers to each month of the water accounting year, beginning 1 July and ending 30 June.
- The *estimate of total dead storage* is 11,000 ML.
- *The volume of carryover* is zero. Note that this means that the level of development is assumed to represent full uptake of entitlement.
- *An estimate of harvestable inflows and pick-up from start of month i to 30 June next* is nil. Note that this is quite conservative as it assumes that there will be no inflows to the WGWSS throughout the year.
- *The measured total amount of water released from headworks from 1 July last to the start of month i* is the sum of all the releases as calculated by the model, at each monthly time-step.
- *The volume of reserve* is subject to the prevailing available water as given in GHD (2011).
- *The estimated headworks losses from the start of month i to 30 June next* is subject to the sum of the volume held in the storages specified in the second bullet point above as per GHD (2011).

Table 3.3 Method for estimating Water Available in the WGWSS (VGG, 2010)

Available water in month i	=	measured total volume in store at the start of month i
	-	estimate of total dead storage
	-	the volume of carryover
	+	an estimate of harvestable inflows and pick-up from start of month i to 30 June next
	+	the measured total amount of water released from headworks from 1 July last to the start of month i
	-	the volume of reserve
	-	the estimated headworks losses from the start of month i to 30 June next

Note: "Month i" refers to each month of the water accounting year beginning 1 July and ending 30 June

In this case, the criterion that would be used to evaluate candidate optimal operating plans with respect to system-wide interests for water is the total system water allocation. Such criteria together with the performance metrics in Section 3.2.4 are incorporated in the formulation of the higher order MOOP by way of objective functions, f_{16} to f_{18} (refer to Section 3.3.1).

3.2.4 Performance metrics

From the discussion of stakeholders' interests for water in Section 3.2.3, the following criteria are suggested as a means to evaluate candidate optimal operating plans:

- *Environmental flow deficits* of 6 EWDs representing environmental interests for water (refer to Section 3.2.3.1);
- *Volume held in storage* at Lake Lonsdale, Lake Fyans, and Rocklands Reservoir representing social interests for water in terms of the provision for recreation amenity at Lake Lonsdale and Lake Fyans and for the maintenance of water quality at Rocklands Reservoir (refer to Section 3.2.3.2);
- *Consumptive user deficits* of 30 consumptive user demands representing consumptive interests for water (refer to Section 3.2.3.3); and
- *Total system water allocations* for the WGWSS representing system-wide interests for water (refer to Section 3.2.3.4).

For these criteria to be incorporated in the higher order MOOP, a suitable unit of measure is required to evaluate candidate optimal operating plans on a quantitative basis with respect to the four interests for water identified (i.e. environmental, social, consumptive, and system-wide interests). These *performance metrics* ought to be comprehensive and aimed at providing the basis for meaningful dialogue amongst the stakeholders and the DM, as required by the planning process. For the purposes of this thesis, it is assumed that the participants require the following information: (i) the frequency of desirable or successful events (i.e. reliability); (ii) the rate of recovery of the WGWSS after undesirable events or failures occur (i.e. resiliency), and (iii) the severity of failures (i.e. vulnerability). It is worth highlighting that Sandoval-Solis et al. (2011) makes reference to several other studies that show that these three performance metrics summarise essential performance parameters in a meaningful manner.

Sections 3.2.4.1 to 3.2.4.3 present these performance metrics (i.e. reliability, resiliency, and vulnerability) in terms of an annual time-period (i.e. July to June) given that this is the preferred basis on which to communicate such information to the community in the WGWSS (DSE, 2011).

3.2.4.1 Reliability

Loucks (1997) defined *reliability* as the probability of successful events over the planning period. In the case of environmental flow deficits (i.e. Section 3.2.3.1) and consumptive user deficits (i.e. Section 3.2.3.3), a successful event is defined as a period of 'nil' deficits. For each time period (t), deficits $(Def_{i,t})$ are positive when the water demand $(D_{i,t})$ is more than the water supplied $(Q_{i,t})$ to the i^{th} interest for water, and when the water supplied is equal to the water demand $(Q_{i,t} = D_{i,t})$ deficits are zero $(Def_{i,t} = 0)$:

$$Def_{i,t} = \begin{cases} D_{i,t} - Q_{i,t}, & \text{if } D_{i,t} > Q_{i,t} \\ 0, & \text{if } D_{i,t} = Q_{i,t} \end{cases} \tag{3.2}$$

Time-based reliability (Rel_i) may be expressed as the portion of time the water demand is fully satisfied $(Def_{i,t} = 0)$ with respect to the number of time intervals (n) considered (McMahon et al., 2006). For this thesis, it is assumed that annual environmental flow deficits $(\sum_{t=1}^{12} Def_{env,t})$ and annual consumptive user deficits

($\sum_{t=1}^{12} Def_{cons,t}$) are required and so n corresponds to the number of years over the model planning period, from 1891 to 2009:

$$Rel_{env} = \frac{\text{No.of years } (\sum_{t=1}^{12} Def_{env,t}) = 0}{n} \text{ , where } n = 118 \text{ years} \tag{3.3}$$

$$Rel_{cons} = \frac{\text{No.of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0}{n} \text{ , where } n = 118 \text{ years} \tag{3.4}$$

In the case of social interests for water (i.e. Section 3.2.3.2), a successful event is defined as a period when the volume held in a storage is greater than the minimum volume that provides the desired level of recreation amenity or water quality as required. For each time period (t), time-based reliability would be expressed as the portion of time the volume held in a storage was greater than the minimum desired volume with respect to the number of time intervals (n) considered. For this thesis, it is assumed that monthly storage volumes are required for Lake Lonsdale ($S_{LL,t}$), Lake Fyans ($S_{LF,t}$), and Rocklands Reservoir ($S_{RR,t}$) and so n corresponds to the number of months over the model planning period, from 1891 to 2009:

$$Rel_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.5}$$

$$Rel_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.6}$$

$$Rel_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.7}$$

In the case of system-wide interests for water (i.e. Section 3.2.3.4), a successful event is defined as a period when the total system water allocation is equal to the full allocation of 97,550 ML. For each time period (t), time-based reliability (Rel_i) would be expressed as the portion of time the total system water allocation is equal to 97,550 ML with respect to the number of time intervals (n) considered. For this thesis, it is assumed that the total system water allocation in June ($W_{system,June}$) is required and so n corresponds to the number of years over the model planning period, from 1891 to 2009:

$$Rel_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML}}{n} \text{, where } n = 118 \text{ years} \tag{3.8}$$

3.2.4.2 Resiliency

Agrell et al. (1998) defined *resiliency* as a system's capacity to adapt to changing conditions i.e. rate of recovery. This is particularly important given that climate conditions are no longer steady. In recent times of prolonged dry conditions (1996 to 2010), storage levels in the WGWSS dropped to unprecedented levels and water carting programs were required to deliver water to users as operating the system under these extreme conditions would result in significant volumes of water lost through seepage and evaporation (DSE, 2011). Hashimoto et al. (1982) described resiliency as the probability that a system recovers from a period of failure. Sandoval-Solis et al. (2011) defined resiliency as the probability of a successful period following a failure period for all failure periods. In the case of environmental flow deficits (i.e. Section 3.2.3.1) and consumptive user deficits (i.e. Section 3.2.3.3), the resiliency would be the probability of 'nil' deficit periods following deficit periods with respect to all deficit periods. As this thesis assumes that annual environmental flow deficits ($\sum_{t=1}^{12} Def_{env,t}$) and annual consumptive user deficits ($\sum_{t=1}^{12} Def_{cons,t}$) are required (refer to Equations 3.3 and 3.4), resiliency is also expressed in terms of the number of years that successful/failure periods occur over the planning period:

$$Res_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{env,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occured}} \quad (3.9)$$

$$Res_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{cons,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occured}} \quad (3.10)$$

In the case of social interests for water (i.e. Section 3.2.3.2), a successful event is defined as a period when the volume held in a storage is greater than the minimum volume that provides the desired level of recreation amenity or water quality as required. Therefore, a failure period is the reverse i.e. when the volume held in a storage is equal to or less than the minimum desired volume. As this thesis assumes that monthly storage volumes are required for Lake Lonsdale ($S_{LL,t}$), Lake Fyans ($S_{LF,t}$), and Rocklands Reservoir ($S_{RR,t}$) (refer to Equations 3.5 to 3.7), resiliency is also expressed in terms of the number of months that successful/failure periods occur over the planning period:

$$Res_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML follows } S_{LL,t} \leq 5{,}379 \text{ ML}}{\text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occured}} \quad (3.11)$$

$$Res_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML follows } S_{LF,t} \leq 1{,}761 \text{ ML}}{\text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occured}} \quad (3.12)$$

$$Res_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML follows } S_{RR,t} \leq 69{,}600 \text{ ML}}{\text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occured}} \tag{3.13}$$

In the case of system-wide interests for water (i.e. Section 3.2.3.4), a successful event is defined as a period when the total system water allocation is equal to the full allocation of 97,550 ML and a failure period is when the total system water allocation is less than the full allocation. As this thesis assumes that the total system water allocation in June ($W_{system,June}$) is required (refer to Equation 3.8), resiliency is also expressed in terms of the total system water allocation in June:

$$Res_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML follows } W_{system,June} < 97{,}550 \text{ ML}}{\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}} \tag{3.14}$$

3.2.4.3 Vulnerability

Hashimoto et al. (1982) defined *vulnerability* as the likely value of failures, if they occur, which effectively describes the severity of failures. High reliability may hide disastrous consequences once a failure has occurred. Agrell et al. (1998) suggested that to measure the severity of a failure, a numerical measure of the most severe outcome during a failure state ought to be used. This has been expressed in a variety of ways including the average failure, the average of maximum failures over all continuous failure periods, and the probability of exceeding a certain failure threshold (Sandoval-Solis et al., 2011). Sandoval-Solis et al. (2011) defined vulnerability as the sum of the failures, divided by the number of times failures occurred. Dimensionless vulnerability is calculated by dividing this average failure by the average of the water demand for that particular interest for water (Sandoval-Solis et al., 2011). In the case of environmental flow deficits (i.e. Section 3.2.3.1) and consumptive user deficits (i.e. Section 3.2.3.3), the vulnerability would be the average deficit divided by the average of the EWDs and consumptive user demands (respectively) over the planning period. As this thesis assumes that annual environmental flow deficits and annual consumptive user deficits are required (refer to Equations 3.3, 3.4, 3.9 and 3.10), vulnerability is also expressed in terms of the number of years that deficits occur over the planning period:

$$Vul_{env} = \frac{(\sum_{t=1}^{12} Def_{env,t}) / \text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{env,t})} \tag{3.15}$$

$$Vul_{cons} = \frac{(\sum_{t=1}^{12} Def_{cons,t}) / \text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{cons,t})} \tag{3.16}$$

In the case of social interests for water (i.e. Section 3.2.3.2), a failure event is defined as a period when the volume held in a storage is equal to or less than the minimum volume that provides the desired level of recreation amenity or water quality as required. Therefore, vulnerability would be the average failure divided by the average volume held in that storage over the planning period. As this thesis assumes that monthly storage volumes are required for Lake Lonsdale ($S_{LL,t}$), Lake Fyans ($S_{LF,t}$), and Rocklands Reservoir ($S_{RR,t}$) (refer to Equations 3.5 to 3.7, and 3.11 to 3.13), vulnerability is also expressed in terms of the number of months that failure periods occur over the planning period:

$$Vul_{LL} = \frac{(\Sigma[\max\{0,(5{,}379 \text{ ML} - S_{LL,t})\}]/\text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occurred}}{\text{Average of } S_{LL,t}} \quad (3.17)$$

$$Vul_{LF} \quad \frac{(\Sigma[\max\{0,(1{,}761 \text{ ML} - S_{LF,t})\}]/\text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occurred}}{\text{Average of } S_{LF,t}} \quad (3.18)$$

$$Vul_{RR} = \frac{(\Sigma[\max\{0,(69{,}600 \text{ ML} - S_{RR,t})\}]/\text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occurred}}{\text{Average of } S_{RR,t}} \quad (3.19)$$

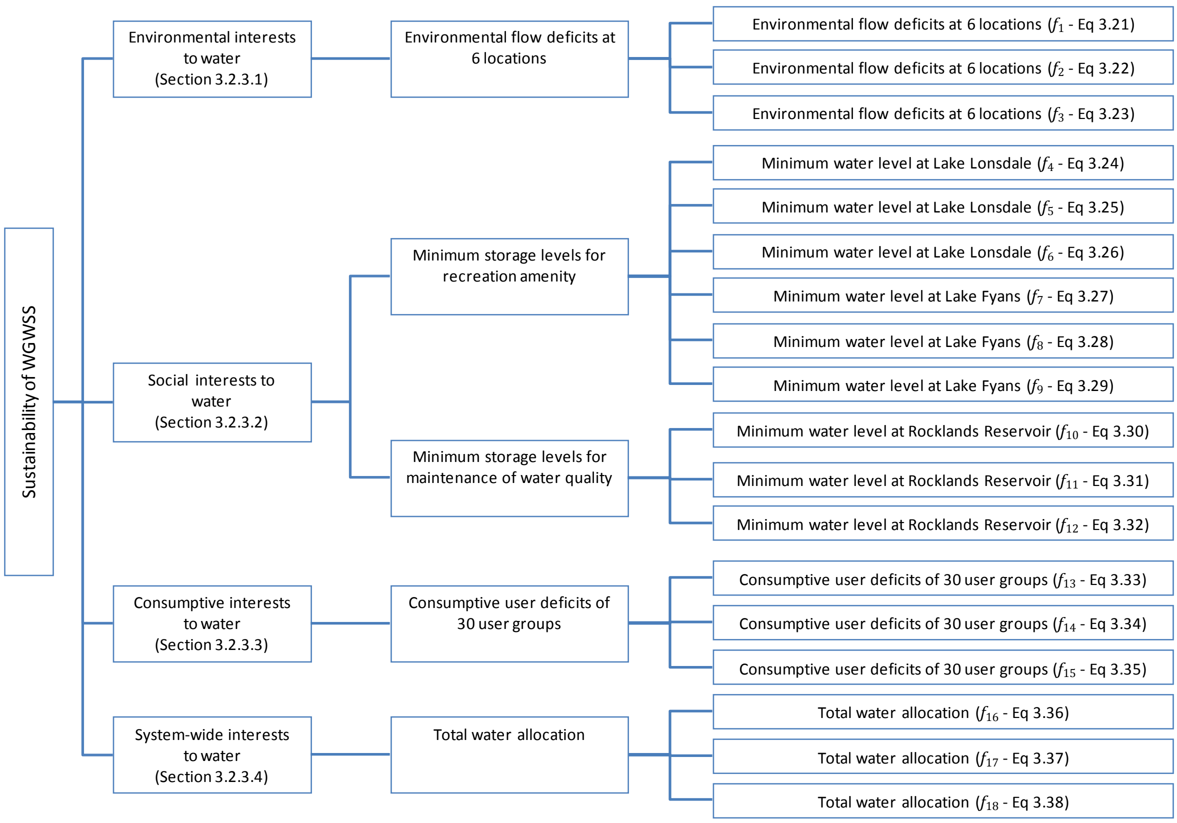
In the case of system-wide interests for water (i.e. Section 3.2.3.4), a failure event is defined as a period when the total system water allocation is less than the full allocation of 97,550 ML. As this thesis assumes that the total system water allocation in June ($W_{system,June}$) is required (refer to Equations 3.8 and 3.14), vulnerability is also expressed in terms of the total system water allocation in June:

$$Vul_{alloc} = \frac{(\Sigma(97{,}550 \text{ ML} - W_{system,June})/\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}}{\text{Average of } W_{system,June}} \quad (3.20)$$

3.3 A higher order MOOP for the Wimmera-Glenelg Water Supply System

Having identified all the major interests for water in Section 3.2, a higher order MOOP is formulated for the WGWSS in Section 3.3 with sustainability as an overall goal. The problem is structured hierarchically using a value tree. Belton and Stewart (2002) state that a value tree is often used in multi-criteria decision making problems to structure the problem on a hierarchical basis with the broad interests towards the top of the tree and the more specific criteria towards the bottom of the tree. For the purposes of this thesis, Figure 3.4 presents the value tree of the higher order MOOP for the WGWSS. For ease of presentation, the top of the tree is shown to the left of the figure and corresponds to the highest level criteria, being in this case, the sustainability of the

WGWSS. The next criteria level down represents the four interests for water identified (i.e. environmental, social, consumptive, and system-wide interests). The third criteria level from the top represents a further clarification and/or breakdown from the four interests for water of the second level.



Note: 'f_m' refers to the m^{th} objective function which is defined in Section 3.3.1

Figure 3.4 Value tree of the higher order MOOP for the WGWSS

For instance, environmental interests for water are expressed in terms of environmental flow deficits at 6 locations and social interests for water are expressed in terms of minimum storage levels for recreation amenity and also maintenance of water quality. The lowest level criteria, or the bottom of the tree, is shown to the right of the figure and represents the underlying conflicts of the problem and are unambiguous and measurable (Belton and Stewart, 2002; Juwana et al., 2012). In this case, the higher order MOOP is structured so that the lowest level criteria represent 18 conflicting objective functions, f_1 to f_{18} (refer to Equations 3.21 to 3.38).

It is worth highlighting that formulating a higher order MOOP using higher criteria levels (e.g. the four interests for water) would have the effect of reducing the dimensionality of the problem whereas lower criteria levels (e.g. the 18 objective functions) would have the reverse effect. Extending this concept to the development of a sustainability index is an important step in the development of a structured procedure for the multi-objective optimisation of complex water resource systems.

3.3.1 Objective functions

With reference to the mathematical expression for a MOOP given in Equation 3.1, the aim in solving the higher order MOOP for this thesis is to find a set of operating rules which minimise/maximise all the objective functions (simultaneously) and which satisfy the constraints of the problem. These objective functions play a role of guiding the optimisation search towards candidate optimal operating plans that perform the best in terms of the values of these objective functions. Moreover, the higher order MOOP for this thesis is structured so that there is a link between the conflicting interests for water in the WGWSS and the optimisation search as given by the value tree of the MOOP in Figure 3.4. The 18 objective functions of the higher order MOOP for this thesis are provided in Equations 3.21 to 3.38. Note that in each case, the time period (t) refers to each month from July to June in line with the water accounting year used in the WGWSS (VGG, 2010).

The 18 objective functions are formulated using the 18 performance metrics presented in Section 3.2.4; with sustainability as an overall goal. The sustainability of the WGWSS is measured in terms of maximising the reliability (Rel_i), maximising the resiliency (Res_i), and minimising the vulnerability (Vul_i) of the i^{th} interest for water. It is worth highlighting that further to the conflicts that exist amongst the four interests for water (i.e. environmental, social, consumptive, and system-wide interests), additional conflicts arise within these individual interests for water. For instance, increasing the performance of the environmental objectives means that there is less water extracted from waterways which reduces the volume available for supply to consumptive users and for provision of recreation amenity, and vice versa. Additionally, within the environmental interests for water, an increase the reliability of nil environmental flow deficits does not necessarily equate to an increase in resiliency; nor does the increase in any or both of these two objectives (i.e. reliability and resiliency) result in reduced vulnerability of such deficits, and vice versa.

3.3.1.1 Environmental

For the criteria in Figure 3.4 representing environmental interests for water, the corresponding objective functions, f_1 to f_3, (Equations 3.21 to 3.23) are based on performance metrics Rel_{env} (Equation 3.3), Res_{env} (Equation 3.9), and Vul_{env} (Equation 3.15) respectively:

$$\text{Maximise}, f_1 = Rel_{env} = \frac{\text{No. of times } Def_{env,t} = 0}{n}, \text{where } n = 118 \text{ years} \quad (3.21)$$

$$\text{Maximise}, f_2 = Res_{env} = \frac{\text{No. of times } Def_{env,t} = 0 \text{ follows } Def_{env,t} > 0}{\text{No. of times } Def_{env,t} > 0 \text{ occured}} \quad (3.22)$$

$$\text{Minimise}, f_3 = Vul_{env} = \frac{(\sum Def_{env,t})/\text{No. of times } Def_{env,t} > 0 \text{ occurred}}{D_{env}} \quad (3.23)$$

3.3.1.2 Social

For the criteria in Figure 3.4 representing social interests for water, the corresponding objective functions, f_4 to f_{12} (Equations 3.24 to 3.32) are based on performance metrics Rel_{LL} (Equation 3.5), Res_{LL} (Equation 3.11), Vul_{LL} (Equation 3.17), Rel_{LF} (Equation 3.6), Res_{LF} (Equation 3.12), Vul_{LF} (Equation 3.18), Rel_{RR} (Equation 3.7), Res_{RR} (Equation 3.13), and Vul_{RR} (Equation 3.19) respectively:

$$\text{Maximise}, f_4 = Rel_{LL} = \frac{\text{No. of times } S_{LL,t} > 5{,}379 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (3.24)$$

$$\text{Maximise}, f_5 = Res_{LL} = \frac{\text{No. of times } S_{LL,t} > 5{,}379 \text{ ML follows } S_{LL,t} \leq 5{,}379 \text{ ML}}{\text{No. of times } S_{LL,t} \leq 5{,}379 \text{ ML occured}} \quad (3.25)$$

$$\text{Minimise}, f_6 = Vul_{LL} = \frac{(\sum[\max\{0,(5{,}379 \text{ ML} - S_{LL,t})\}]/\text{No. of times } S_{LL,t} \leq 5{,}379 \text{ ML occurred}}{mean\ (S_{LL,t})} \quad (3.26)$$

$$\text{Maximise}, f_7 = Rel_{LF} = \frac{\text{No. of times } S_{LF,t} > 1{,}761 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (3.27)$$

$$\text{Maximise}, f_8 = Res_{LF} = \frac{\text{No. of times } S_{LF,t} > 1{,}761 \text{ ML follows } S_{LF,t} \leq 1{,}761 \text{ ML}}{\text{No. of times } S_{LF,t} \leq 1{,}761 \text{ ML occured}} \quad (3.28)$$

$$\text{Minimise}, f_9 = Vul_{LF} \quad \frac{(\sum[\max\{0,(1{,}761 \text{ ML} - S_{LF,t})\}]/\text{No. of times } S_{LF,t} \leq 1{,}761 \text{ ML occurred}}{mean\ (S_{LF,t})} \quad (3.29)$$

$$\text{Maximise}, f_{10} = Rel_{RR} = \frac{\text{No. of times } S_{RR,t} > 69{,}600 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (3.30)$$

$$\text{Maximise}, f_{11} = Res_{RR} = \frac{\text{No. of times } S_{RR,t} > 69{,}600 \text{ ML follows } S_{RR,t} \leq 69{,}600 \text{ ML}}{\text{No. of times } S_{RR,t} \leq 69{,}600 \text{ ML occured}} \quad (3.31)$$

$$\text{Minimise}, f_{12} = Vul_{RR} = \frac{(\sum[\max\{0,(69{,}600 \text{ ML} - S_{RR,t})\}]/\text{No. of times } S_{RR,t} \leq 69{,}600 \text{ ML occurred}}{mean\ (S_{RR,t})} \quad (3.32)$$

3.3.1.3 Consumptive

For the criteria in Figure 3.4 representing consumptive interests for water, the corresponding objective functions, f_{13} to f_{15} (Equations 3.33 to 3.35) are based on performance metrics Rel_{cons} (Equation 3.4), Res_{cons} (Equation 3.10), and Vul_{cons} (Equation 3.16) respectively:

$$\text{Maximise}, f_{13} = Rel_{cons} = \frac{\text{No. of times } Def_{cons,t} = 0}{n}, \text{ where } n = 118 \text{ years} \tag{3.33}$$

$$\text{Maximise}, f_{14} = Res_{cons} = \frac{\text{No. of times } Def_{cons,t} = 0 \text{ follows } Def_{cons,t} > 0}{\text{No. of times } Def_{cons,t} > 0 \text{ occured}} \tag{3.34}$$

$$\text{Minimise}, f_{15} = Vul_{cons} = \frac{(\sum Def_{cons,t})/\text{No. of times } Def_{cons,t} > 0 \text{ occurred}}{D_{cons}} \tag{3.35}$$

3.3.1.4 System-wide

For the criteria in Figure 3.4 representing system-wide interests for water, the corresponding objective functions, f_{16} to f_{18} (Equations 3.36 to 3.38) are based on performance metrics Rel_{alloc} (Equation 3.8), Res_{alloc} (Equation 3.14), and Vul_{alloc} (Equation 3.20) respectively:

$$\text{Maximise}, f_{16} = Rel_{alloc} = \frac{\text{No. of times } W_{system,June} = 97{,}550 \text{ ML}}{n}, \text{ where } n = 118 \text{ years} \tag{3.36}$$

$$\text{Maximise}, f_{17} = Res_{alloc} = \frac{\text{No. of times } W_{system,June} = 97{,}550 \text{ ML follows } W_{system,June} < 97{,}550 \text{ ML}}{\text{No. of times } W_{system,June} < 97{,}550 \text{ ML occurred}} \tag{3.37}$$

$$\text{Minimise}, f_{18} = Vul_{alloc} = \frac{(\sum(97{,}550 \text{ ML} - W_{system,June})/\text{No. of times } W_{system,June} < 97{,}550 \text{ ML occurred}}{mean\,(W_{system,June})} \tag{3.38}$$

3.3.2 Decision variables

With reference to the mathematical expression for a MOOP given in Equation 3.1, the aim in solving the higher order MOOP for this thesis is to find decision variable values that satisfy the constraints of the problem and which minimises/maximises all the objective functions, simultaneously. For this thesis, it is assumed that the decision variables for the higher order MOOP are expressed in terms of 24 water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. The planning decisions are categorised into six areas of system operation, viz.; (i) *priorities of supply* between different sources of supply and between different user groups; (ii) a *storage flood reserve volume* to provide flood attenuation; (iii) *environmental allocation shares* for apportioning environmental water allocations between river basins; (iv) the preference of alternative *flow paths* for the harvesting and/or transfer of water; (v) *storage maximum operating volumes* for the key water harvesting storages; and (vi) *storage draw down priorities and storage targets*. Table 3.4 provides a summary of the 24 water management planning decisions which collectively are referred to as an "operating plan" in this thesis.

Table 3.4 Water management planning decisions for the WGWSS

Category	dv_x	Decisions	Value range
Priority of supply	dv_1	Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?	Either Lake Wartook or Moora Moora Reservoir is first priority and the other is a supplementary source of supply
	dv_2	Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?	Either Horsham (1) or EWD (2) is satisfied first
	dv_3	Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?	Either harvest flows into Taylors Lake or EWD (3) is satisfied first
	dv_4	Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?	Either harvest flows into Taylors Lake or EWD (4) is satisfied first
	dv_5	Should consumptive demands (6) to (9) be satisfied before the EWDs in Glenelg River (1) or vice versa?	Either consumptive demands (6) to (9) or EWD (1) is satisfied first
	dv_6	Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir or vice versa?	Either harvest flows into WIC or provide passing flow first
	dv_7	Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?	Either hold water in Lake Lonsdale for consumptive demands (19) to (30) or supply EWD (5) first
Flood reserve volume	dv_8	How much flood reserve should be provided at Lake Wartook over the period April to September?	Either hold no reserve or hold a maximum of up to the full storage capacity in June
Share of environ-mental allocation	dv_9	How much of the environmental water allocation should be released in the Glenelg River basin?	Either no share or up to 100% of the environmental water allocation
	dv_{10}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Wartook?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin
	dv_{11}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Lonsdale?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin and that at Lake Wartook
Flow path	dv_{12}	Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?	Either harvest flows into Wimmera Inlet Channel or pass all flows to Wimmera River
	dv_{13}	Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?	Supply from Lake Bellfield may result in one of three outcomes; nil, a proportion based on the volume in storage, or 100%
Storage maximum operating volume	dv_{14}	Toolondo Reservoir	0 to 92,430 ML
	dv_{15}	Lake Lonsdale	Inlet is either open or closed
	dv_{16}	Lake Bellfield	0 to 76,000 ML
	dv_{17}	Taylors Lake	0 to 33,700 ML
	dv_{18}	Rocklands Reservoir	0 to 348,000 ML
	dv_{19}	Lake Lonsdale	0 to 65,000 ML
	dv_{20}	Moora Moora Reservoir	0 to 6,300 ML
Storage draw down priority and storage target	dv_{21}	What should be the drawdown priority of the headworks storages?	Each storage is assigned a unique draw down priority from 1 to 8
	dv_{22}	What should be the second point on the target curve for the headworks storages?	Any volume between dead storage and FSL
	dv_{23}	What should be the third point on the target curve for the headworks storages?	Any volume between the second target point and FSL
	dv_{24}	What should be the fourth point on the target curve for the headworks storages?	Any volume between the third target point and FSL

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
'EWDs' refers to environmental water demands.
Number in brackets refers to consumptive user demand centres and environmental flow sites shown in Figure 3.2.

Each sub-section under Section 3.3.2 presents the six categories of system operation in terms of the mathematical equations that are configured in the Wimmera-Glenelg REALM model. The Wimmera-Glenelg REALM model consists of *nodes* representing diversion structures, reservoirs, and water demands which are connected with *carriers* which represent waterways, channels and pipes within the WGWSS (refer to Figure 3.3). In REALM, the preferred flow distribution is determined by user-defined penalties in the carriers. When there is a choice of flow paths, the carrier with the lowest penalty will transfer flow up to the user-specified capacity, then the carrier with the next higher penalty will be used and so on until the demand for water at the downstream node is satisfied. A wide range of operating rules can be configured in the model by using variable capacity carriers in which mathematical equations are expressed in terms of an *x-y* relationship, where *y* represents the capacity of the carrier at a given simulation time-step and *x* is a function of any number of system variables such as carrier flow/capacity, water demand, and reservoir volume etc. Alternatively the user can exploit the functional attributes of the nodes and carriers within the model to represent more conventional rules/constraints such as a minimum flow carrier capacity representing environmental minimum flow requirements in a waterway. Further details regarding the operation of REALM is provided in Section 2.2.4.1. Note that words in upper case font refer to node and carrier names within the Wimmera-Glenelg REALM model.

3.3.2.1 Priority of supply

There are seven planning decisions regarding the priority of supply between different sources of supply and between different user groups within the WGWSS. With the exception of dv_1 (Equation 3.39) which relates to the priority of supply between different sources of supply, dv_2 to dv_7 (Equations 3.40 to 3.45) relate to the priority of supply between different user groups.

a) *Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?*

   Carrier MACKENZIE RIV U represents the MacKenzie River reach between EWDs (2) and (3) as shown in Figure 3.2. This carrier is used to set the priority of supply between water that is available from Moora Moora Reservoir and Lake Wartook for supply to consumptive demands (2) to (5) and EWDs (3) and (4). When the penalty of MACKENZIE RIV U is equal to 6,000,000, the preferred supply path is from Moora Moora Reservoir and when this penalty is equal to 0 the preferred supply path is from Lake Wartook. Hence a decision variable value of either 0 or 1 is used for dv_1 to provide these two penalties in carrier MACKENZIE RIV U as follows:

$$\text{Penalty of carrier MACKENZIE RIV U} = dv_1 \times 6{,}000{,}000 \qquad (3.39)$$

Where,

dv_1 = 0 or 1 (note: a value of 1 is used in the base case operating plan)

b) *Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?*

Carrier MPF UPPER MAC represents the MacKenzie River reach between EWDs (2) and (3) as shown in Figure 3.2. Note that this carrier is included in the Wimmera-Glenelg REALM model for the purposes of providing environmental flows in the reach and is separate from carrier MACKENZIE RIV U (refer to Section 3.3.2.1a). Carrier MPF UPPER MAC is used to set the priority of supply between EWD (2) and consumptive user (1) which represents Horsham. When the penalty of MPF UPPER MAC is equal to -54,000,000, the preferred demand is EWD (2) and when this penalty is equal to -5,000,000 the preferred demand is consumptive user (1). Hence a decision variable value of either 0 or 1 is used for dv_2 to provide these two penalties in carrier MPF UPPER MAC as follows:

$$\text{Penalty of carrier MPF UPPER MAC} = (dv_2 \times 49{,}000{,}000) - 54{,}000{,}000 \qquad (3.40)$$

Where,

dv_2 = 0 or 1 (note: a value of 0 is used in the base case operating plan)

c) *Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?*

Carrier MPF LOWER MAC represents the MacKenzie River reach between EWD (3) and the Wimmera River confluence as shown in Figure 3.2. This carrier is used to set the priority of supply between EWD (3) and those EWDs and consumptive users (19) to (30) supplied via Taylors Lake. When the penalty of MPF LOWER MAC is equal to -54,001,000 the preferred demand is EWD (3) and when this penalty is equal to -5,001,000 the preferred demands are those supplied via Taylors Lake. Hence a decision variable value of either 0 or 1 is used for dv_3 to provide these two penalties in carrier MPF LOWER MAC as follows:

$$\text{Penalty of carrier MPF LOWER MAC} = (dv_3 \times 49{,}000{,}000) - 54{,}001{,}000 \qquad (3.41)$$

Where,

dv_3 = 0 or 1 (note: a value of 0 is used in the base case operating plan)

d) *Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?*

Carrier MPF BURNT represents the Burnt Creek reach between EWD (4) and the Wimmera River confluence as shown in Figure 3.2. This carrier is used to set the priority of supply between EWD (4) and those EWDs and consumptive users (19) to (30) supplied via Taylors Lake. When the penalty of MPF BURNT is equal to -54,000,500 the preferred demand is EWD (4) and when this penalty is equal to -5,000,500 the preferred demands are those supplied via Taylors Lake. Hence a decision variable value of either 0 or 1 is used for dv_4 to provide these two penalties in carrier MPF BURNT as follows:

$$\text{Penalty of carrier MPF BURNT} = (dv_4 \times 49{,}000{,}000) - 54{,}000{,}500 \qquad (3.42)$$

Where,

dv_4 = 0 or 1 (note: a value of 1 is used in the base case operating plan)

e) *Should consumptive demands (6) to (9) be satisfied before the EWDs in Glenelg River (1) or vice versa?*

Carrier MPF GLEN represents the Glenelg River reach downstream of Rocklands Reservoir as shown in Figure 3.2. This carrier is used to set the priority of supply between EWD (1) and consumptive users (6) to (9) supplied via Rocklands Reservoir. When the penalty of MPF GLEN is equal to -54,000,000 the preferred demand is the EWD and when this penalty is equal to -5,000,000 the preferred demands are the consumptive users. Hence a decision variable value of either 0 or 1 is used for dv_5 to provide these two penalties in carrier MPF GLEN as follows:

$$\text{Penalty of carrier MPF GLEN} = (dv_5 \times 49{,}000{,}000) - 54{,}000{,}000 \quad (3.43)$$

Where,

dv_5 = 0 or 1 (note: a value of 0 is used in the base case operating plan)

f) *Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir or vice versa?*

Carrier HUDDLE WMP ENV represents the Wimmera River reach between the diversion structure (known as "Huddlestons Weir") and the Mt William Creek confluence as shown in Figure 3.2. This carrier is used to set the priority of supply between the passing flow provided at Huddlestons Weir and those EWDs and consumptive users (19) to (30) supplied via Taylors Lake (from water that is harvested from the Wimmera River). When the penalty of HUDDLE WMP ENV is equal to -54,001,000 the preferred demand is the passing flow and when this penalty is equal to -5,001,000 the preferred demands are those supplied via Taylors Lake. Hence a decision variable value of either 0 or 1 is used for dv_6 to provide these two penalties in carrier HUDDLE WMP ENV as follows:

$$\text{Penalty of carrier HUDDLE WMP ENV} = (dv_6 \times 49{,}000{,}000) - 54{,}001{,}000 \quad (3.44)$$

Where,

dv_6 = 0 or 1 (note: a value of 0 is used in the base case operating plan)

g) *Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?*

Carrier MPF MT WILL represents the Mt William Creek reach between Lake Lonsdale and the Wimmera River confluence as shown in Figure 3.2. This carrier is used to set the priority of supply between EWD (5) and consumptive users (19) to (30) supplied via Taylors Lake (from Mt William Creek flow that is intercepted by the open channel known as the "Wimmera Inlet Channel").

When the penalty of MPF MT WILL is equal to -54,000,000 the preferred demand is the EWD and when this penalty is equal to -5,000,000 the preferred demands are those supplied via Taylors Lake. Hence a decision variable value of either 0 or 1 is used for dv_7 to provide these two penalties in carrier MPF MT WILL as follows:

$$\text{Penalty of carrier MPF MT WILL} = (dv_7 \times 49{,}000{,}000) - 54{,}000{,}000 \qquad (3.45)$$

Where,

dv_7 = 0 or 1 (note: a value of 0 is used in the base case operating plan)

3.3.2.2 Flood reserve volume

Lake Wartook is operated to provide some degree of flood attenuation whilst at the same time ensuring a very good chance of filling over the April to September period. Over the long term, a flood reserve volume that is too large may affect the supply to users downstream, and a reserve volume that is too small may cause the storage to overflow more often and result in more water being lost (in an operational sense) from the system (Godoy et al., 2011).

a) *How much flood reserve should be provided at Lake Wartook over the period April to September?*

The flood reserve volume at Lake Wartook is provided by carrier TOT FLOOD WARTOOK which represents the MacKenzie River reach between Lake Wartook and EWD (2) as shown in Figure 3.2. In any month (*t*) during the period April to September, this carrier forces a release from the storage equal to the volume of water that exceeds the flood target volume (FTV_t). Hence a decision variable value of between 0 and 1 is used for dv_8 to calculate a flood target volume in June (FTV_{Jun}) which serves as the basis for a flood target curve over the period April to September as follows:

$$\text{Flood target volume (Jun)},\ FTV_{Jun} = dv_8 \times \text{FSL} \qquad (3.46)$$

$$\text{Flood reserve volume (Jun)},\ FRV_{Jun} = \text{FSL} - FTV_{Jun} \qquad (3.47)$$

Where,

$0 \leq dv_8 \leq 1$ (note: a value of 0.7 is used in the base case operating plan)

$\text{FSL} = 29{,}356 \text{ ML}$

The flood target curve is determined from FTV_{Jun} as follows:

$$\text{Flood target volume (Apr, Sep)} = FTV_{Jun} + [(\text{FSL} - FTV_{Jun})/1.2] \quad (3.48)$$

$$\text{Flood target volume (May, Aug)} = FTV_{Jun} + [(\text{FSL} - FTV_{Jun})/2] \quad (3.49)$$

$$\text{Flood target volume (Jul)} = FTV_{Jun} + [(\text{FSL} - FTV_{Jun})/5] \quad (3.50)$$

Figure 3.5 shows the Lake Wartook flood target curve corresponding to the largest possible reserve volume (i.e. $dv_8 = 0, FTV_{Jun} = 0 \text{ ML}, FRV_{Jun} = 29{,}356 \text{ ML}$), the reserve volume used in the base case operating plan (i.e. $dv_8 = 0.7, FTV_{Jun} = 20{,}549 \text{ ML}, FRV_{Jun} = 8{,}807 \text{ ML}$), and the smallest possible reserve volume ($dv_8 = 1, FTV_{Jun} = 29{,}356 \text{ ML}, FRV_{Jun} = 0$).

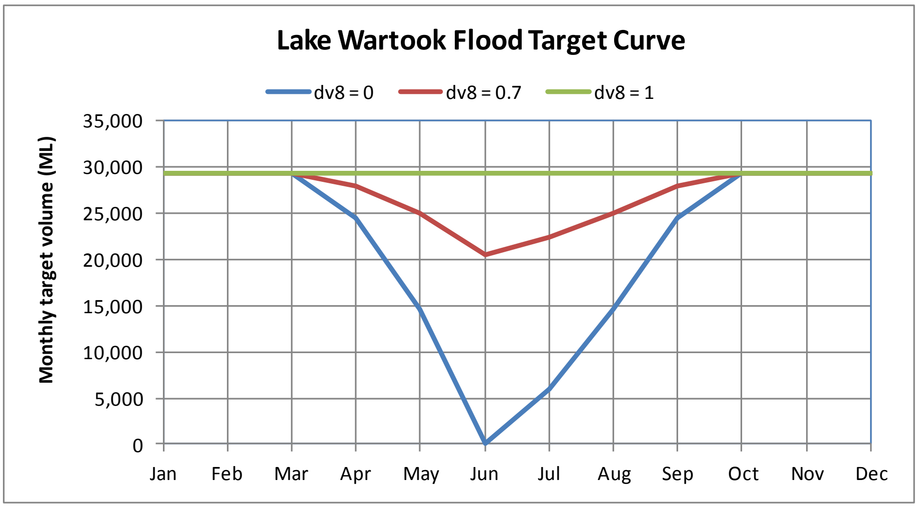


Figure 3.5 Lake Wartook flood target curve

3.3.2.3 <u>Share of environmental allocation</u>

Environmental water that is available from storage in the WGWSS (referred to as "regulated" flow) is allocated to the Glenelg and Wimmera river basins as constant shares of 40% and 60% respectively (GHD, 2011). Godoy and Barton (2011) explained that these shares had an effect on the efficiency of the WGWSS and on the composition of the environmental entitlement in terms of the regulated flow and the amount passed at diversion structures (referred to as “unregulated” flow). The authors showed that the environmental entitlement would be more effective if it were formulated with a smaller volumetric and higher reliability regulated entitlement instead of a larger volumetric and lower reliability regulated entitlement. This is of particular interest to the environment during water shortages when unregulated flows are scarce and there are higher levels of competition for regulated water.

The maximum annual (regulated) environmental allocation is 41,560 ML in the WGWSS (refer to “Environment” in Table 3.2). However, for modelling purposes the 1,000 ML allocation for supply to wetlands is aggregated together with GWMWater’s recreation allocation of 2,590 ML and is not considered to be water for environmental purposes. This is consistent with DELWP’s REALM model, WMPP2104.sys (refer to Section 3.2.2). Whilst the remaining 40,560 ML allocation is the subject of the environmental allocation shares presented in this thesis (i.e. dv_9 to dv_{11}), changes to these shares affect the efficiency of the WGWSS as explained earlier in this section.

The 40,560 ML allocation is released at four locations within the headworks, namely; the Glenelg River at Rocklands Reservoir (i.e. dv_9), MacKenzie River at Lake Wartook (i.e. dv_{10}), Mt William Creek at Lake Lonsdale (i.e. dv_{11}), and the Wimmera River at Taylors Lake. Note that the Taylors Lake environmental allocation share is by default the remaining share of the environmental allocation after that provided at Rocklands Reservoir, Lake Wartook, and Lake Lonsdale.

a) *How much of the environmental water allocation should be released in the Glenelg River basin?*

   The environmental water allocation in the Glenelg River basin is provided from Rocklands Reservoir via carrier REG GLENELG R which represents the Glenelg River reach between the storage and EWD (1) as shown in Figure 3.2. Note that this carrier is only used when there is any residual environmental water demand at EWD (1) after unregulated flows have been exhausted (i.e. passing flows and spills at Rocklands Reservoir). Hence a decision variable value of between 0 and 1 is used for dv_9 to determine the allocation share in the

Glenelg River basin by setting the capacity of REG GLENELG R equal to the Glenelg basin share (GBS), as follows:

$$\text{Glenelg basin share}, GBS = dv_9 \times 40{,}560 \tag{3.51}$$

Where,

$$0 \leq dv_9 \leq 1 \text{ (note: a value of 0.4 is used in the base case operating plan)}$$

b) *How much of the environmental water allocation should be released in the Wimmera River basin at Lake Wartook?*

The environmental water allocation in the MacKenzie River is provided from Lake Wartook via carrier REG MACKENZIE R which represents the MacKenzie River reach between the storage and EWD (2) as shown in Figure 3.2. Note that this carrier is only used when there is any residual environmental water demand at EWDs (2), (3), (4) and (6) after unregulated flows have been exhausted (i.e. spills at Lake Wartook, Lake Bellfield, Lake Fyans, and Lake Lonsdale including any overland catchment flows intercepted by streams downstream of these storages). Hence a decision variable value of between 0 and 1 is used for dv_{10} to determine the allocation share from Lake Wartook by setting the capacity of REG MACKENZIE R equal to the Wimmera basin share at Lake Wartook (WBS_{LW}), as follows:

$$\text{Wimmera basin share}, WBS = (1 - dv_9) \times 40{,}560 \tag{3.52}$$

$$\text{Wimmera basin share at Lake Wartook}, \ WBS_{LW} = dv_{10} \times WBS \tag{3.53}$$

Where,

$$0 \leq dv_{10} \leq 1 \text{ (note: a value of 0.3 is used in the base case operating plan)}$$

c) *How much of the environmental water allocation should be released in the Wimmera River basin at Lake Lonsdale?*

The environmental water allocation in Mt William Creek is provided from Lake Lonsdale via carrier REG MT WILL CK which represents Mt William Creek reach between the storage and EWD (5) as shown in Figure 3.2. Note that this carrier is only used when there is any residual environmental water demand at EWDs (5) and (6) after unregulated flows have been exhausted (i.e. spills at

Lake Wartook, Lake Bellfield, Lake Fyans, and Lake Lonsdale including any overland catchment flows intercepted by streams downstream of these storages). Hence a decision variable value of between 0 and 1 is used for dv_{11} to determine the allocation share from Lake Lonsdale by setting the capacity of REG MT WILL CK equal to the Wimmera basin share at Lake Lonsdale (WBS_{LL}), as follows:

Wimmera basin share excluding Lake Wartook,

$$WBS_{ex\ LW} = (1 - dv_{10})\ \times WBS \tag{3.54}$$

Wimmera basin share at Lake Lonsdale,

$$WBS_{LL} = \min\left[(dv_{11} \times WBS), WBS_{ex\ LW}\ \right] \tag{3.55}$$

Where,

$0\ \leq dv_{11}\ \leq 1$ (note: a value of 0.6 is used in the base case operating plan)

Note that the environmental water allocation provided at Taylors Lake is deterministic without the need for a decision variable:

Wimmera basin share at Taylors Lake,

$$WBS_{TL} = \max\left[0, \{(1 - dv_{10} - \ dv_{11}) \times WBS\ \}\ \right] \tag{3.56}$$

3.3.2.4 Flow path

The planning decisions relating to the flow path for the harvesting and/or transferring of water represent two contentious issues that were gleaned from the available stakeholder information as part of the desktop study referred to in Section 3.2.3. Whilst the first contention relates to the operation of Lake Lonsdale and the second contention to the operation of Lake Bellfield, the two issues are related in a sense given they involve the operation of the eastern part of the WGWSS.

By way of background to the first contention, the water entitlements in the WGWSS require that the operating arrangements for the system be developed by agreement between the entitlement holders and the operator (VGG, 2010). These operating arrangements were set out in GWMWater (2011) which stated that Lake Lonsdale was a "key" source of water for the environment. Lake Lonsdale is an on-stream storage located in the eastern part of the WGWSS on Mt William Creek, as shown in Figure 3.2. Moreover, a management plan for Lake Lonsdale which was prepared by the operator (i.e. GWMWater) in consultation with community members stated that the “primary” role of Lake Lonsdale was for provision of environmental flows (GWMWater, 2012a). However, the *2012-13 Seasonal Watering Plan* stated that the “preferred” storage for environmental flows was Taylors Lake (VEWH, 2013). From this literature, there appears to be two main reasons for this contention:

- That Lake Lonsdale is the most inefficient storage of the headworks and that whilst the Mt William Creek catchment is high yielding in some years, the cost of the evaporative losses outweighs the revenue generated from its use as a water supply source for consumptive users. Note that the Victorian Environmental Water Holder (VEWH) does not contribute financially towards the operation of Lake Lonsdale, provided it does not issue instructions to GWMWater to operate the storage outside of the operational bounds set out in GWMWater (2011); and
- That the water quality in Lake Lonsdale is generally of poorer quality than that naturally occurring downstream of the storage. This is presumably the reason for VEWH (2013) preferring Taylors Lake for the release of environmental flows, and also that efforts at that time (at Taylors Lake) were being made to improve water quality for consumptive users supplied via the Wimmera Mallee Pipeline (WMP).

In this case, the contentious issue relating to the operation of Lake Lonsdale is represented by decision variables which specify (i) the flow path taken by releases from Lake Lonsdale to either meet EWDs or consumptive use (i.e. dv_{12}); and (ii) the storage maximum operating volume for Lake Lonsdale (refer to dv_{15} and dv_{19} under Section 3.3.2.5).

a) *Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?*

   Carrier MT WILLIAM TO HUDDLE represents the Mt William Creek reach between EWD (5) and the open channel that is intercepted by the creek known as the “Wimmera Inlet Channel” as shown in Figure 3.2. This carrier is used to set the flow path of Mt William Creek flows for supply to EWD (5) or to consumptive users (19) to (30) supplied via Taylors Lake. When the penalty of MT WILLIAM TO HUDDLE is equal to 550,100 the preferred flow path is to supply the EWD and when this penalty is equal to 100 the preferred flow path is to consumptive users via the Wimmera Inlet Channel. Hence a decision variable value of either 0 or 1 is used for dv_{12} to provide these two penalties in carrier MT WILLIAM TO HUDDLE as follows:

$$\text{Penalty of carrier MT WILLIAM TO HUDDLE} = (dv_{12} \times 550{,}000) + 100 \tag{3.57}$$

Where,

dv_{12} = 0 or 1 (note: a value of 0 is used in the base case operating plan)

The second contentious issue which relates to the operation of Lake Bellfield, is mainly to do with the water quality issues that arise when mixing water sourced from Lake Bellfield with that stored in Taylors Lake for supply to consumptive users (19) to (30) shown in Figure 3.2. The purpose for building a direct transfer from Lake Bellfield to Taylors Lake (known as the “Bellfield-Taylors pipeline”) was to reduce the transmission loss which would have occurred along Fyans Creek and Mt William Creek and to regulate the supply to consumptive users via the Wimmera Mallee Pipeline (in terms of volume and water quality). Historically, Lake Bellfield has had excellent water quality however following the recent 2011 flood event in the region, the Lake Bellfield catchment has become fragile in the sense that it is more susceptible to increased sediment loads from intense rainfall events. The base case operating plan provides for Lake Bellfield to be operated just below full supply in order to allow for reasonable volumes of (assumed) good quality water to flush what may be at times poorer quality water through the storage (GWMWater, 2011). The water that is routed through Lake Bellfield is directed to Lake Fyans and Lake Lonsdale wherever airspace exists. The term *airspace* is used in this thesis to describe the volumetric difference between a storage’s full supply volume and the volume held in that storage. Importantly, this routing of water through Lake Fyans and Lake Lonsdale reduces the risk of blue-green algae blooms in these storages (GWMWater, 2012a; 2012b). In contrast to Lake Bellfield, Taylors Lake has historically suffered from elevated salinity and turbidity levels associated with the harvesting of water from the Wimmera River. To complicate matters further, Mt William Creek below Lake Lonsdale is known for its good water quality and is preferentially harvested into Taylors Lake, where as water held in Lake Lonsdale can often be of relatively poor quality which means that releases can interfere with the operation of Taylors Lake. The contention exists between the following interests for water in that they all would prefer high levels of water quality: environmental flows at EWD (5) *versus* social interests for water at Lake Fyans and Lake Lonsdale in terms of reducing the risk of blue-green algae blooms *versus* consumptive users (19) to (30).

It is important to highlight that as the Wimmera-Glenelg REALM model is not setup to account for such water quality parameters (e.g. salinity, turbidity etc), this thesis focuses on the (storage) operation of the WGWSS in so far as managing water quality is concerned. Based on the information above, it is assumed that there is a choice of three alternative flow paths that relate to the transfer of water from Lake Bellfield to Taylors Lake viz. two alternative flow paths that use the Bellfield-Taylors pipeline; and one alternative flow path that does not use the pipeline. Of the two alternative flow paths that use the pipeline, one regulates the transfer volume according to the relative storage targets and drawdown priorities for Lake Bellfield and Taylors Lake (refer to Equations 3.61 to 3.64); the other corresponds to that under the base case operating plan which regulates the transfer volume subject to the volume held in Lake Bellfield. The alternative flow path that does not use the Bellfield-Taylors pipeline uses Fyans Creek and Mt William Creek to transfer water from Lake Bellfield to Taylors Lake. Table 3.5 presents the relationship between the volume held in Lake Bellfield in November each year and the share of water supplied from the storage to the consump-

Table 3.5 Relationship between the volume held in Lake Bellfield versus the proportion supplied to consumptive users (19) to (30) via the Bellfield-Taylors pipeline (as per the base case operating plan)

Volume (ML) held in Lake Bellfield in November	Proportion (%) supplied to consumptive users (19) to (30) via the Bellfield-Taylors pipeline*
0	0
10,000	0
10,001	40
15,000	40
15,001	50
24,000	50
24,001	60
33,000	60
33,001	100
76,000	100

*Consumptive users (19) to (30) and the Bellfield-Taylors pipeline are shown in Figure 3.2

-tive users as given under the base case operating plan. Note that the share is held constant from November of the previous year to October of the current year for each year of the planning period.

b) *Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?*

Carrier BELL TAY PIPE represents the Bellfield-Taylors pipeline and its transfer capacity is dependent on one of three values given by carrier BELL TO WMP MIX. Each of these values or "carrier capacities" correspond to one of the three alternative flow paths which can be used to transfer water from Lake Bellfield to Taylors Lake as described above. When the value given by BELL TO WMP MIX is '0' the transfer capacity of BELL TAY PIPE is subject to the relative storage targets and drawdown priorities for Lake Bellfield and Taylors Lake. When the value given by BELL TO WMP MIX is '1' the transfer capacity of BELL TAY PIPE is 'nil' which means the Bellfield-Taylors pipeline is not used. When the value given by BELL TO WMP MIX is '2' the transfer capacity of BELL TAY PIPE is subject to the the proportion given in Table 3.5. Hence a decision variable value of either 0, 1, or 2 is used for dv_{13} to provide these three values equal to the capacity of carrier BELL TO WMP MIX, as follows:

$$\text{Capacity of carrier BELL TO WMP MIX } = dv_{13} \quad (3.58)$$

Where,

$dv_{13} = 0,$ means that up to 100% of the consumptive demands of (19) to (30) is sourced from Lake Bellfield subject to the relative storage targets and drawdown priorities for Lake Bellfield and Taylors Lake (refer to Equations 3.61 to 3.64);

$dv_{13} = 1,$ means that water from Lake Bellfield is not transferred to Taylors Lake via the Bellfield-Taylors pipeline. Note that Lake Bellfield can still make releases to consumptive users (19) to (30) via Fyans Creek and Mt William Creek provided that the flow path from Mt William Creek to the Wimmera Inlet Channel allows for such to occur (refer to Equation 3.57); and

$dv_{13} = 2,$ means that the proportion described in Table 3.5 is supplied to consumptive users (19) to (30) via the Bellfield-Taylors pipeline and that

Taylors Lake would provide the balance of these consumptive demands. Note that this is the value used in the base case operating plan.

3.3.2.5 Storage maximum operating volume

A maximum operating volume is used to specify the upper most limit of a storage's airspace for a variety of reasons, which may include the provision of environmental (unregulated) flows; to reduce storage evaporative losses; and to preserve the structural integrity of a storage (GWMWater, 2011). It is assumed that a maximum operating volume is required at 6 of the 12 headworks storages viz. Toolondo Reservoir, Lake Bellfield, Taylors Lake, Rocklands Reservoir, Lake Lonsdale, and Moora Moora Reservoir. Note the Wimmera-Glenelg REALM model assumes that the other 6 headworks storages (i.e. Lake Fyans, Lake Wartook, Horsham storages, Dock Lake, Green Lake, and Pine Lake) are operated to their respective full supply volumes as specified in Table 3.1. When the volume held in the (former) storages exceed the specified maximum operating volume, either no more water is allowed to enter the storage or; the storage is drained to the specified maximum operating volume as required by the storage's inlet/outlet configuration.

a) *What should be the maximum operating volumes for Toolondo Reservoir, Lake Bellfield, Taylors Lake, Rocklands Reservoir, Lake Lonsdale, and Moora Moora Reservoir?*

A value of between 0 and 1 is used to specify the maximum operating volume for the decision variables (dv_x) in terms of the proportion of the full supply volume of the j^{th} storage ($S_{j,FSV}$), as follows:

$$\text{Maximum operating volume for the } j^{th} \text{ storage} = dv_x \times S_{j,FSV} \qquad (3.59)$$

Where,

$0 \leq dv_x \leq 1$ (note: decision variables (dv_x) as specified in Table 3.6)
$S_{j,FSV}$ = full supply volume of the j^{th} storage as specified in Table 3.6

Table 3.6 Decision variables (dv_x) and corresponding full supply volume ($S_{j,FSV}$) for six headworks storages in the WGWSS

Decision variable, dv_x	j^{th} storage (S_j)	Full Supply Volume, $S_{j,FSV}$ (ML)
dv_{14}	Toolondo Reservoir	92,430
dv_{16}	Lake Bellfield	76,000
dv_{17}	Taylors Lake	33,700
dv_{18}	Rocklands Reservoir	348,000
dv_{19}	Lake Lonsdale	65,000
dv_{20}	Moora Moora Reservoir	6,300

dv_{15} is not included as it alone does not represent a storage maximum operating volume

Unlike the other storages in Table 3.6, Lake Lonsdale has its own catchment and a bypass channel which means that the maximum operating volume requires two decision variables; one for the outlet (refer to decision variable dv_{19}, in Equation 3.59) and another for the inlet (refer to decision variable dv_{15}, in Equation 3.60) Carrier 2ND DIV CHNL is used to represent the Lake Lonsdale inlet channel. When the capacity of 2ND DIV CHNL is 'nil' the inlet channel is closed and so any water from upstream storages (i.e. Lake Fyans and Lake Bellfield) and any overland pickup flows are bypassed around Lake Lonsdale. When the capacity of 2ND DIV CHNL is greater than zero, the inlet channel allows Lake Lonsdale to fill up to the maximum operating volume (i.e. decision variable dv_{19}, refer to Equation 3.59) or the storage target volume (refer to Equations 3.62 to 3.64), whichever is the lesser. Hence a decision variable value of either 0 or 1 is used for dv_{15} to specify the capacity of carrier 2ND DIV CHNL as follows:

$$\text{Capacity of carrier 2ND DIV CHNL} = dv_{15} \tag{3.60}$$

Where,

$dv_{15} = 0$, means that the Lake Lonsdale inlet channel is closed. Note that this is the value used in the base case operating plan;

$dv_{15} = 1$, means that the Lake Lonsdale inlet channel is open and allows the storage to fill up to the maximum operating volume (i.e. decision variable dv_{19}, refer to Equation 3.59) or the storage target volume (refer to Equations 3.62 to 3.64), whichever is the lesser.

3.3.2.6 Storage target and draw down priority

The Wimmera-Glenelg REALM model uses storage targets to describe the broad operation of the system in terms of the sharing of the available resource amongst the various headworks storages at any given month of the year. In addition to storage targets, a relative draw down priority is also specified for each storage so that under a situation of limited resource, water is sourced from the preferred storage(s) (Godoy et al., 2011). Table 3.7 summarises the draw down priorities for the 12 headworks storages in terms of three *supply systems* as given under the base case operating plan.

Table 3.7 Supply systems and draw down priorities for the headworks storages of the WGWSS (as per the base case operating plan)

Supply system	j^{th} storage (S_j)	Draw down priority*
0	Lake Lonsdale	na
	Pine Lake	
	Dock Lake	
	Green Lake	
1	Moora Moora Reservoir	1
	Lake Wartook	2
	Horsham storages	3
2	Toolondo Reservoir	4
	Taylors Lake	5
	Lake Bellfield	6
	Lake Fyans	7
	Rocklands Reservoir	8

* Draw down priority denoted dv_{21,S_j} - refer Equation 3.61

'na' refers to storages in supply system (0) which do not require relative draw down priorities given that these are the first to be drawn down with respect to all 12 storages in the WGWSS

With reference to Figure 3.2, the j^{th} storage (S_j) is assigned to one of the three supply systems as shown below. Note that in each case the storages are listed in order of first to be drawn down (i.e. the highest draw down priority '1' to the lowest draw down priority '8'):

- Supply system (0) means that Lake Lonsdale, Pine Lake, Dock Lake, and Green Lake are the first to be drawn down with respect to all 12 storages in the WGWSS;
- Supply system (1) corresponds to the relative draw down priorities of Moora Moora Reservoir, Lake Wartook, and the Horsham storages with respect to the supply to consumptive users (1) to (5); and
- Supply system (2) corresponds to the relative draw down priorities of Toolondo Reservoir, Taylors Lake, Lake Bellfield, Lake Fyans, and Rocklands Reservoir with respect to the supply to consumptive users (6) to (30).

Note that the storages in supply system (0) do not require draw down priorities as these are the first storages to be drawn down with respect to all 12 storages. Note also that the draw down priorities in supply systems (1) and (2) are independent of each other.

a) *What should be the draw down priority of the headworks storages?*

The draw down priority of the j^{th} storage (S_j) for decision variable dv_{21,S_j} is expressed as follows:

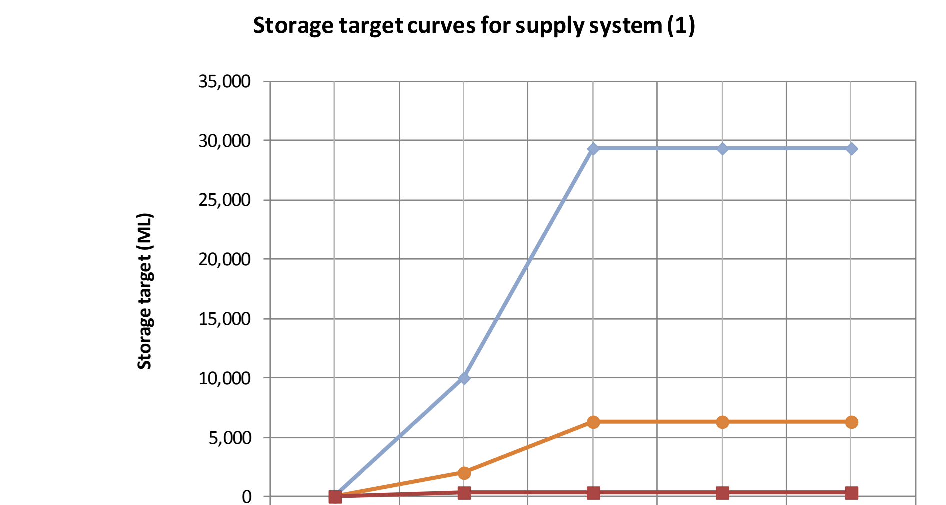
$$\text{Draw down priority of the } j^{th} \text{ storage } (S_j) = dv_{21,S_j} \tag{3.61}$$

Where,

$dv_{21,S_j} = 1, 2, 3, \ldots$ or 8 (refer to Table 3.7 for the values used in the base case operating plan)

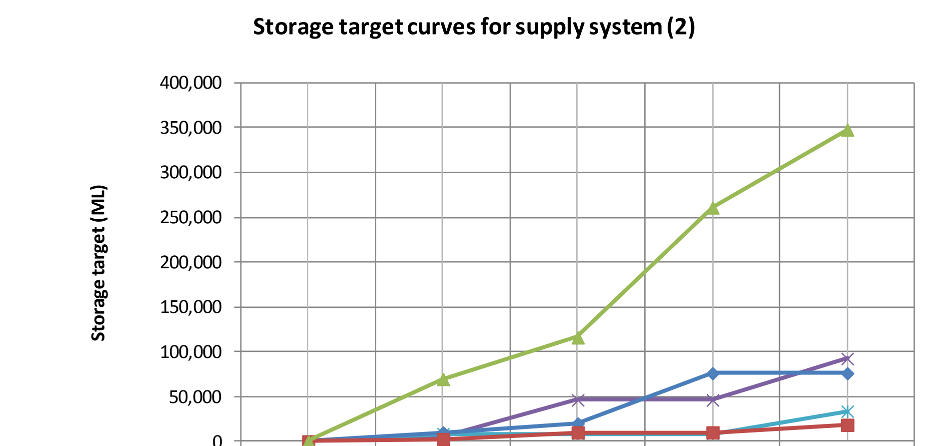
S_j refers to the storages listed in Table 3.7

The Wimmera-Glenelg REALM model specifies the storage targets in terms of 5 points along a storage target curve where the first storage target is 'nil' (i.e. dead storage) and the fifth storage target corresponds to the full supply volume given in Table 3.1. This means that the second, third and fourth storage targets need to be specified as the first and fifth storage targets are known. Figure 3.6 and Figure 3.7 summarise the storage target curves under the base case operating plan for supply systems (1) and (2) respectively. Note that the storage target curves for supply system (0) are not shown given that these storages (i.e. Lake Lonsdale, Pine Lake, Dock Lake, and Green Lake) are the first to be drawn down with respect to all 12 storages in the WGWSS.



	0	12328	35988	35988	35988
Moora Moora Reservoir	0	2000	6300	6300	6300
Lake Wartook	0	10000	29360	29360	29360
Horsham storages	0	328	328	328	328

Figure 3.6 Storage target curves for supply system (1) (as per the base case operating plan)



	0	82100	146000	347000	442460
Toolondo Reservoir	0	5000	46250	46250	92430
Taylors Lake	0	8500	8500	8500	33700
Lake Bellfield	0	10000	20000	76000	76000
Lake Fyans	0	2500	10000	10000	18460
Rocklands Reservoir	0	69600	116000	261000	348000

Figure 3.7 Storage target curves for supply system (2) (as per the base case operating plan)

b) *What should be the second point on the target curve for the headworks storages?*

For the second point on the target curve (TC_{2,S_j}), a value of between 0 and 1 is used used for dv_{22,S_j} to describe the proportion of the j^{th} storage's (S_j) volume between the inaccessible volume or "dead storage" ($S_{j,dead}$) and that storage's full supply volume ($S_{j,FSV}$) as follows:

$$\text{Second point on target curve, } TC_{2,S_j} = dv_{22,S_j} \times S_{j,FSV} \quad (3.62)$$

Where,

$0 \leq dv_{22,S_j} \leq 1$ (note: the values used in the base case operating plan are specified in Table 3.8)

c) *What should be the third point on the target curve for the headworks storages?*

For the third point on the target curve (TC_{3,S_j}), a value of between 0 and 1 is used for dv_{23,S_j} to describe the proportion of the j^{th} storage's (S_j) volume between the second point on the target curve (TC_{2,S_j}) and that storage's full supply volume ($S_{j,FSV}$) as follows:

$$\text{Third point on target curve, } TC_{3,S_j} = [dv_{23,S_j} \times (S_{j,FSV} - TC_{2,S_j})] + TC_{2,S_j} \quad (3.63)$$

Where,

$0 \leq dv_{23,S_j} \leq 1$ (note: the values used in the base case operating plan are specified in Table 3.8)

d) *What should be the fourth point on the target curve for the headworks storages?*

For the fourth point on the target curve (TC_{4,S_j}), a value of between 0 and 1 is used used for dv_{24,S_j} to describe the proportion of the j^{th} storage's (S_j) volume between the third point on the target curve (TC_{3,S_j}) and that storage's full supply volume ($S_{j,FSV}$) as follows:

Fourth point on target curve, $TC_{4,S_j} = [dv_{24,S_j} \times (S_{j,FSV} - TC_{3,S_j})] + TC_{3,S_j}$ (3.64)

Where,

$0 \leq dv_{24,S_j} \leq 1$ (note: the values used in the base case operating plan are specified in Table 3.8)

Table 3.8 provides a summary of the second, third and fourth points of the target curves for those storages that pertain to supply system (1) and (2) under the base case operating plan. Note that six decimal places are required in order to achieve the storage target volume to the nearest megalitre.

Table 3.8 Second, third and fourth points of the storage target curves expressed in terms of decision variables values, dv_{22,S_j}, dv_{23,S_j} and dv_{24,S_j} (as per the base case operating plan)

Supply system	j^{th} storage (S_j)[1]	Target curve points expressed in terms of decision variable values		
		Second point (dv_{22,S_j})[1]	Third point (dv_{23,S_j})[2]	Fourth point (dv_{24,S_j})[3]
1	Moora Moora Reservoir	0.317460	1.000000	0.000000
	Lake Wartook	0.341297	1.000000	0.000000
	Horsham storages	1.000000	0.000000	0.000000
2	Toolondo Reservoir	0.054095	0.471806	0.000000
	Taylors Lake	0.313653	0.000000	0.000000
	Lake Bellfield	0.127291	0.145858	1.000000
	Lake Fyans	0.135428	0.469925	0.000000
	Rocklands Reservoir	0.199828	0.166487	0.624193

1. Second point of target curve (refer to Equation 3.62)
2. Third point of target curve (refer Equation 3.63)
3. Fourth point of target curve (refer Equation 3.64)

3.3.3 Constraints

With reference to the mathematical expression for a MOOP given in Equation 3.1, the aim in solving the higher order MOOP for this thesis is to find a set of operating rules that satisfy the constraints of the problem and which minimises/maximises all the objective functions, simultaneously. For this thesis, the constraints of the problem are specified both in terms of the formulation of the MOOP (i.e. as bounds on variables and as integer constraints) and also in terms of the real-world limitations of the WGWSS (i.e. as statutory constraints and as physical constraints). By far, most of the problem constraints are configured in the Wimmera-Glenelg REALM model which highlights one of the major benefits of using an O-S modelling approach. That is, many of the complexities of a real-world water resource system may already be configured in simulation models that are trusted by water managers given the many years of model development.

3.3.3.1 Bounds on variables

The upper and lower bounds of the decision variables were provided in Section 3.3.2. A lower bound of 0 and an upper bound of 1 are used in the following planning decisions:

- *flood reserve volume* for Lake Wartook - refer to Equations 3.46 to 3.50;
- *shares of environmental allocation* for the Glenelg and Wimmera river basins - refer to Equations 3.51 to 3.56;
- *storage maximum operating volumes* for Toolondo Reservoir, Lake Bellfield, Taylors Lake, Rocklands Reservoir, Lake Lonsdale, and Moora Moora Reservoir - refer to Equation 3.59; and
- *storage targets* for supply systems (1) and (2) – refer to Equations 3.62 to 3.64.

3.3.3.2 Integer constraints

Integer constraints in the form of binary integer variables (i.e. 0 or 1) were specified for the following planning decisions in Section 3.3.2:

- *priorities of supply* between different sources of supply and between different user group - refer to Equations 3.39 to 3.45;
- *flow path* of Mt William Creek flows, either into Wimmera Inlet Channel or passed down to the Wimmera River – refer to Equation 3.57; and
- as part of the specification of the *storage maximum operating volume* for Lake Lonsdale, in terms of the inlet channel to the storage - refer to Equation 3.60.

3.3.3.3 Statutory constraints

The statutory constraints of the WGWSS are specified in the Wimmera-Glenelg REALM model in terms of the water allocations that are permitted under the Wimmera-Glenelg bulk water entitlements (VGG, 2010). Section 3.2.3.4 explained in detail the method for computing an entitlement holders' share of the available resources together with the relevant modelling assumptions for the purposes of describing the system-wide interests for water.

3.3.3.4 Physical constraints

In addition to the statutory constraints above, the Wimmera-Glenelg REALM model also includes the physical characteristics of all the key assets of the WGWSS in terms of the following:

- the inaccessible storage volume or "dead storage" volume and the full supply volume;
- storage rating curve for the purposes of computing the net evaporation off the water surface (i.e. storage water level versus surface area); and
- transfer capacity of stream reaches, open channels, and pipes.

A full listing of these constraints is provided in GHD (2011).

3.4 Optimisation-simulation model setup

The O-S model that is used to solve the higher order MOOP described in Section 3.3 comprises an optimisation engine and a simulation engine. The optimisation engine uses the Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) and the simulation engine uses the REALM software package. Figure 3.8 shows that the O-S modelling procedure starts with an initial population of randomly generated operating plans (shown as a green shaded circle). The modelling process is iterative; REALM simulation outputs are used to calculate 18 performance metrics (for each plan in the population) which are in turn passed to the NSGA-II to solve for the higher order MOOP of the WGWSS. The O-S model continues to iterate towards a population of optimal operating plans (shown as a red shaded circle in Figure 3.8) until convergence has been achieved or the stopping criterion has been reached. Many researchers describe this iterative process as one of *searching* or *finding* candidate optimal solutions. For this thesis, the O-S model is used to find candidate optimal operating plans which minimise/maximise all the objective functions (simultaneously) and which satisfy the constraints of the problem. The genetic operators (i.e. selection, crossover, and mutation) of the NSGA-II are used to perturb the population of candidate optimal operating plans in order to create new and possibly better performing operating plans compared to those in previous generations.

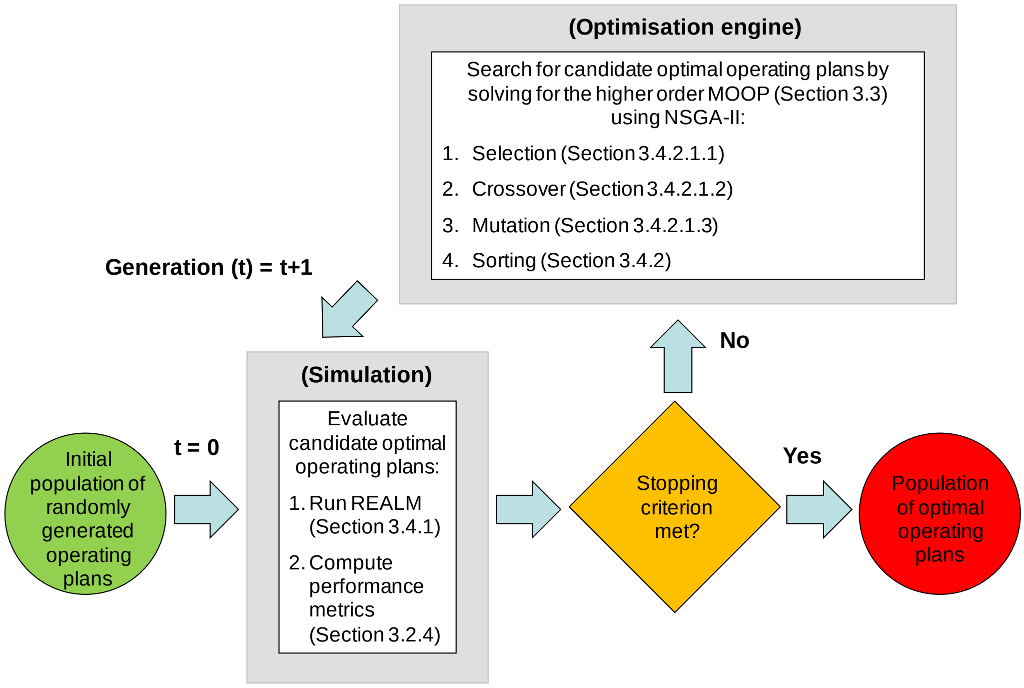


Figure 3.8 Flow chart of optimisation-simulation model used to solve the higher order MOOP for the WGWSS

As the O-S modelling procedure begins with the use of the simulation engine in the first instance, the setup of REALM is presented first in Section 3.4.1 followed by the setup of NSGA-II in Section 3.4.2. The simulation engine is described in terms of the Wimmera-Glenelg REALM model and the input data files for the hydro-climatic data and the water demands. For the purposes of this thesis, three hydro-climatic scenarios are presented representing historic conditions (over the period 1891 to 2009) and two greenhouse gas (GHG) emission scenarios. The two GHG emission scenarios represent the lower and higher ends of the estimated range of GHG emissions as given by the Intergovernmental Panel on Climate Change or IPCC (IPCC, 2000). The “low to medium level” and “medium to high level” GHG emission scenarios selected are estimated to result in total cumulative global carbon dioxide emissions ranging from approximately 800 GtC to 1,400 GtC and 1,400 GtC to 2,000 GtC by 2100 respectively (IPCC, 2000). The units GtC means gigatonnes of carbon.

For the purposes of executing the O-S model, a computer program was written in the MATrix LABoratory (MATLAB) programming language (MathWorks, 2010). Note that the REALM software package was the only part of the O-S model which was not written in MATLAB. The computing tasks performed by this MATLAB program are summarised as follows:

- Setting up the Wimmera-Glenelg REALM model with respect to the 24 decision variable values (i.e. operating plan) described in Section 3.3.2 for each simulation run;
- Executing the REALM software package with the Wimmera-Glenelg REALM model and data input files as described in Section 3.4.1;
- Extracting the required simulation outputs for the purposes of solving the 18 performance metrics described in Section 3.2.4; and
- Executing the NSGA-II as described in Section 3.4.2.

3.4.1 Simulation engine

As shown in Figure 3.8 the simulation engine is comprised of the REsource ALlocation Model (REALM) software package. REALM is a structured computer software package that simulates the harvesting and bulk distribution of water resources within a water supply system (Perera et al., 2005). REALM was the software of choice for this thesis given the following reasons:

- The availability of a calibrated REALM model of the WGWSS which had been developed over the last 20 years and was a well-trusted simulation tool that had been used in major water resource planning studies in Victoria, Australia (refer to Section 3.2.2);
- At the time of commencement of this thesis in 2010, the use of REALM as a simulation engine had not been tested as part of an O-S modelling procedure. Since that time Kularathna et al. (2011) successfully used REALM as the simulation engine and the NSGA-II as the optimisation engine for an O-S modelling study of the Melbourne Water Supply System in Victoria, Australia.

3.4.1.1 System file

The origins of the simulation model developed for this thesis begin with a REALM model provided by the Department of Environment, Land, Water and Planning (DELWP) in 2010 (pers. comm. Michael Finger). The DELWP identified this model or *system file* as it is referred to in REALM, as the “WMPP2104.sys file.” Figure 3.9 shows the WMPP2104.sys file as seen through the graphical editor window in the REALM software package. Note that this graphical representation is very similar to the schematic of the WGWSS shown in Figure 3.2. For the reader’s convenience, the headworks storages of the WGWSS are noted in Figure 3.9. Note that the arrow heads in the centre of the carriers show the direction of flow.

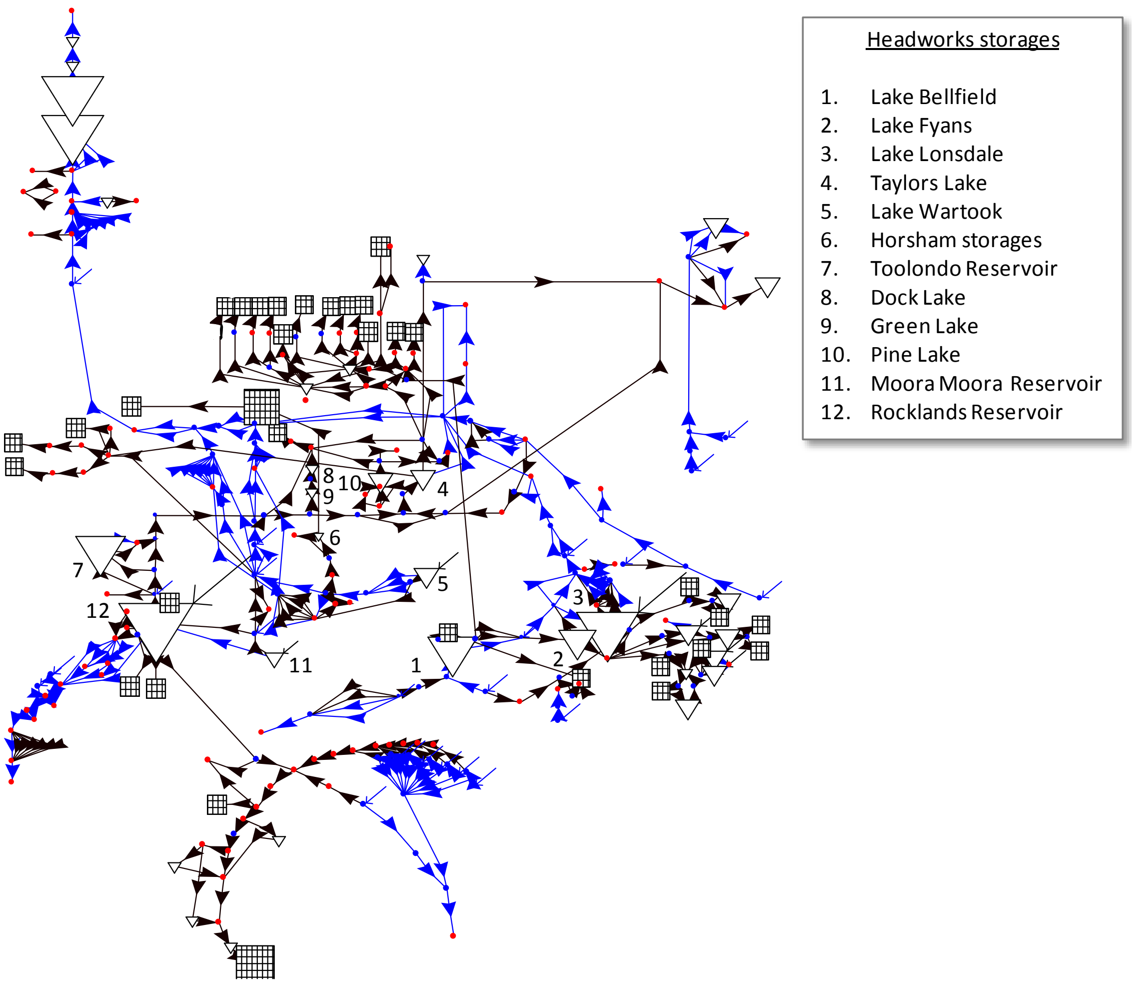


Figure 3.9 The WMPP2104.sys file

Many parts of the WMPP2104.sys file were in a sense *hard-coded* to work in a particular way, according to current practice in the WGWSS. As explained in Section 3.2.2, this set of operating rules is referred to as the “the base case operating plan” in this thesis. This rigid model setup was discovered by way of results which showed that the search for candidate optimal operating plans was localised and not far reaching or *global* across the objective space i.e. quite similar to the base case operating plan. Additionally, the WMPP2104.sys file was not setup to exchange information between it and the optimisation engine. That is, the WMPP2104.sys file required modifications to allow (i) the simulation engine outputs to be used as inputs to the optimisation engine (for evaluation of the 18 performance metrics described in Section 3.2.4); and (ii) for the new candidate optimal operating plans (created by the optimisation engine) to be used as inputs to the simulation engine.

Surrogate models have proven to be useful tools to address the needs described above (Razavi et al., 2012). Razavi et al. (2012) described two types of surrogate models that have been primarily used for the purposes of minimising the computational effort required to run the original simulation model viz. *response surface* models and *lower fidelity* models. The aim of a surrogate model is to approximate the response of an original simulation model. The term *response* refers to the variables of interest which typically form a nonlinear hyperplane called a *response surface*. The term *fidelity* is used in this modelling context to refer to the degree of realism of a simulation model. For example, in the context of this thesis the response surface could be interpreted as the volume of water held in the headworks storages or the flow at a point of interest in the system, over time. In which case, an acceptable surrogate model of the WGWSS would be one that matches (to some acceptable degree) the output data provided by the WMPP2104.sys file.

Response surface models use approximation techniques to fit the response surface of the original models. There are a variety of such techniques some of which include polynomials, kriging, k nearest neighbours, and artificial neural networks. Lower fidelity models share a physical basis to the original simulation model preserving the main functionality; but are less detailed. One key benefit of interest to this thesis is that such *lower-fidelity physically based surrogate models* tend to better emulate the unexplored regions of the decision space compared to response surface models (Razavi et al., 2012). This is important as the search for new operating plans means that the surrogate model would need to search regions that are far from the previously evaluated design sites provided by the original model. For this reason, a lower-fidelity physically based surrogate model of the WGWSS was developed for the purposes of addressing the improvements required to the WMPP2104.sys file described earlier in this section.

This surrogate model is referred to as the “Wimmera-Glenelg REALM model” in this thesis. Thus, the WMPP2104.sys file is considered to be a first level of abstraction (or higher-fidelity) and the Wimmera-Glenelg REALM model is a second level of abstraction (or lower-fidelity). Figure 3.3 shows the Wimmera-Glenelg REALM model as seen through the graphical editor window in the REALM software package. Note that this is the same representation as shown in Figure 3.3. It is obvious from a visual comparison of the WMPP2104.sys file (Figure 3.9) and the Wimmera-Glenelg REALM model, that the latter model configuration is similar in terms of the physical layout of the WMPP2104.sys file, but with a reduced number of storages, carriers and nodes.

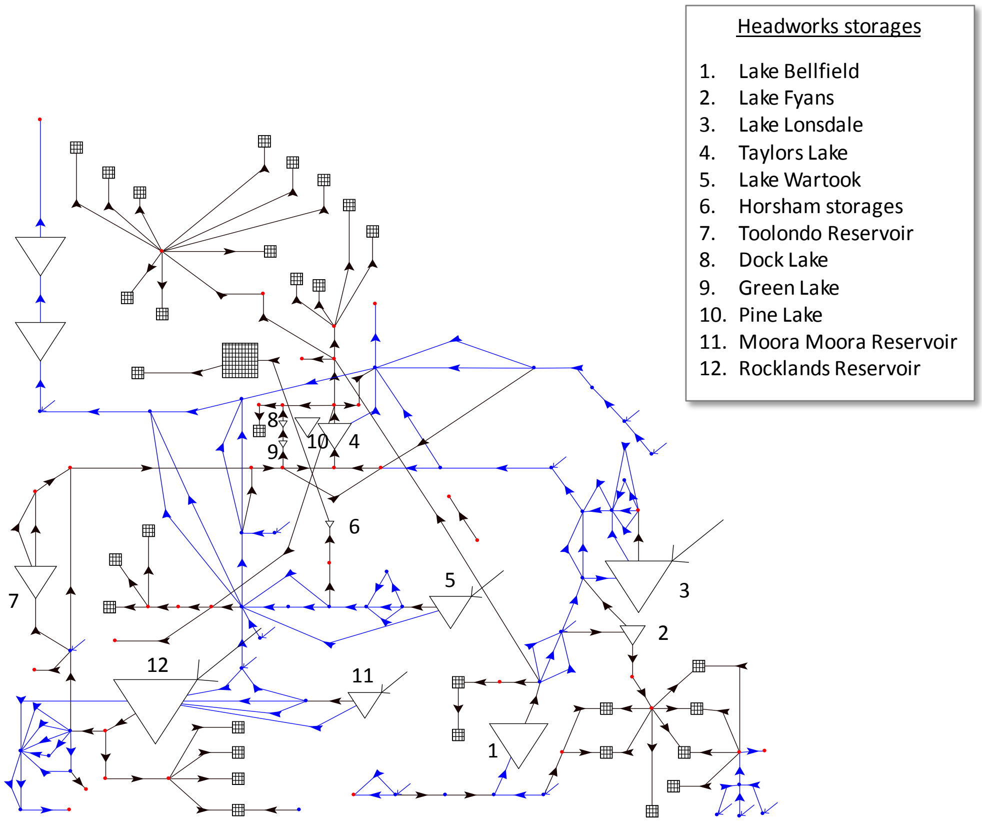


Figure 3.10 The Wimmera-Glenelg REALM model

The Wimmera-Glenelg REALM model was developed by copying the physical network from the WMPP2104.sys file; storage by storage, carrier by carrier, and node by node. In each case, the attributes of the storages, carriers and the nodes configured in the WMPP2104.sys file were questioned in terms of their ability to adapt to changes in the prevailing operating plan. In most cases the storage/carrier/node was simply copied across to the Wimmera-Glenelg REALM model whilst in others, changes were made to their attributes to improve model flexibility (e.g. simplification of mathematical equations). Moreover, sections of the WMPP2104.sys file that were considered superfluous or did not significantly affect the operation of the headworks, were simply not included. In general, these included terminal lakes and small urban water supply storages.

The most significant difference between the WMPP2104.sys file and the Wimmera-Glenelg REALM model was the revision to many of the carrier penalties which were interfering with the storage targets. Refer to Section 3.3.2.6 for further details regarding the storage targets. In general, these penalties were observed to override the storage targets and so cause some model instability (i.e. the number of convergence failures is markedly reduced in the Wimmera-Glenelg REALM model compared to the WMPP2104.sys file). Note that a failure of a REALM model converging to a solution is an indication that the model setup is not stable. Testing was also undertaken at each major stage of model development in terms of trying bookend values for all 24 decision variables presented in Table 3.4. Moreover during its development, the Wimmera-Glenelg REALM model was routinely tested under the two GHG emission scenarios in order to confirm model stability in terms of (simulation) solution convergence. Given the various aforementioned changes, the Wimmera-Glenelg REALM model is not expected to exactly replicate the system behaviour produced by WMPP2104.sys.

The response surface used to fit the Wimmera-Glenelg REALM model to the WMPP2104.sys file was the volume held the headworks storages over the period January 1891 to December 2008. Given that the hydro-climatic inputs and water demands were the same for both models, meant that the model error would largely appear over time in terms of the volume held the headworks storages. Figure 3.11 is a comparison of the WMPP2104.sys file and the Wimmera-Glenelg REALM model in terms of the total volume held in the headworks storages at the end of each monthly time-step, over the period January 1891 to December 2008. Refer to Table 3.1 for details regarding the headworks storages. In general, the time-series data for the Wimmera-Glenelg REALM model fits well with the behaviour exhibited by the WMPP2104.sys file, both during wet periods and dry periods.

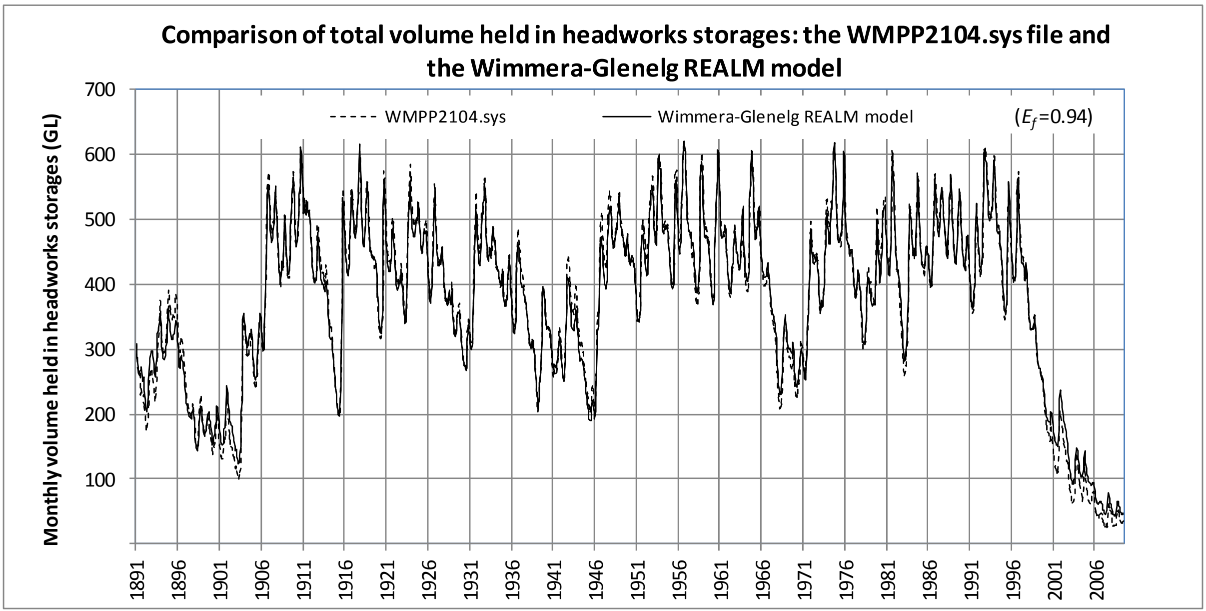


Figure 3.11 Comparison of total volume held in headworks storages

The Nash-Sutcliffe efficiency index (E_f) is widely used for assessing the goodness of fit of hydrologic models (McCuen et al., 2006). Equation 3.65 compares the original model (i.e. WMPP2104.sys) and the revised model (i.e. the Wimmera-Glenelg REALM model) in terms of the total system storage volume at each time-step, month t, as follows:

$$E_f = 1 - \frac{\sum_{t=1}^{T}(S_t^o - S_t^r)^2}{\sum_{t=1}^{T}(S_t^o - \acute{S}_t^o)^2} \qquad (3.65)$$

Where,

$-\propto \; \leq E_f \geq 1$ (note: $E_f = 1$ means a perfect match of the Wimmera-Glenelg REALM model with the WMPP2104.sys file);

S_t^o = Total system storage at month (t) of the WMPP2104.sys file;

S_t^r = Total system storage at month (t) of the Wimmera-Glenelg REALM model;

$\acute{s}_t^o$ = average of the total system storage for month (t = 1, 2, 3,....T) of the WMPP2104.sys file; and

T = 1,416 months from January 1891 to December 2008 inclusive.

Note that the resulting $E_f = 0.94$ means that the Wimmera-Glenelg REALM model is representative of WMPP2104.sys.

3.4.1.2 Input data

The Wimmera-Glenelg REALM model requires the following input data in order for it to be executed:

- 9 rainfall inputs, 18 evaporation inputs, and 21 streamflow inputs which represent one of three hydro-climatic conditions, being either historic, low to medium level, or medium to high level GHG emissions;
- 30 consumptive water demands which collectively represent the upper annual limit of the consumptive water allocation, being 55,990 ML (refer Section 3.2.3.4), subject to the available resources in any given year; and
- 6 environment water demands (EWDs) which collectively represent the upper annual limit of the environmental water allocation, being 41,560 ML (refer Section 3.2.3.4).

3.4.1.2.1 Hydro-climatic inputs

a) Historic

The rainfall, evaporation, and streamflow data sets that represent historic conditions were derived using a methodology that has been developed and refined over the last two decades (HydroTechnology, 1995; SKM, 2004; GHD, 2011; Godoy Consulting, 2013). The 9 rainfall and 18 evaporation data sets are used to represent the effects of rainfall and evaporation at the various water storages and in some cases used to derive consumptive water demands and streamflows. These climatic data sets were derived using mostly recorded data in-filled with interpolated data where recorded data was of poor quality or non-existent. The 21 streamflow data sets represent inflows to storages and weirs, and catchment flows intercepted by streams and channels. These streamflows were derived by either (i) direct use of observed streamflows in the first instance subject to the availability of good quality records; (ii) water balance using a combination of observed streamflows, rainfall, and/or evaporation as required; (iii) rainfall-runoff model; or (iv) regression analysis using observed streamflows at a nearby/representative site.

b) Low to medium level and medium to high level GHG emissions

The two GHG emission scenarios presented in this thesis were developed as part of a separate PhD study at Victoria University (Sachindra, 2014), also relating to the WGWSS. Sachindra (2014) developed various models for the purposes of statistically downscaling coarse atmospheric data to produce rainfall, evaporation, and streamflow data sets at the catchment level. The atmospheric data was sourced from the outputs of general circulation models (GCMs) which are widely used for the projection of global climate into the future. GCMs are based on the fundamentals of physics that describe the climate of the Earth. For the present thesis, the outputs of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the Hadley Centre Coupled Model version 3 General Circulation Model (HadCM3) were used as these produced the best calibration and validation results (Sachindra et al., 2014a). Moreover, these GCM outputs were corrected for any bias using the tested procedure developed by Sachindra et al. (2014b). To derive projections of global climate into the future, these GCMs were fed data inputs that corresponded to a range of concentrations of atmospheric GHGs according to *storylines* that describe different levels of development in terms of demographic, socio-economic and technological change into the future (IPCC, 2000). For the present thesis, storylines B1 and A2 representing the lower and higher ends of the estimated range of GHG emissions are chosen. The motivation for choosing these bookend estimates is that the search for candidate optimal operating plans would be undertaken over the widest plausible range of future hydro-climatic conditions. The "low to medium level" and "medium to high level" GHG emission scenarios selected are estimated to result in total cumulative global carbon dioxide emissions ranging from approximately 800 GtC to 1,400 GtC and 1,400 GtC to 2,000 GtC by 2100 respectively (IPCC, 2000). The units GtC means gigatonnes of carbon.

3.4.1.2.2 Water demands

The location of the 30 consumptive demands and 6 EWDs configured in the Wimmera-Glenelg REALM model are shown in Figure 3.2. The consumptive water demands are stationary and have a seasonal pattern representing the typical increase and decrease of water demand during the summer and winter periods respectively (Godoy Consulting, 2013). The EWDs have a more sophisticated setup in the Wimmera-Glenelg REALM model. The EWD input data represents the stationary, seasonally varying demand which was derived from environmental flow studies of the Wimmera and Glenelg river systems (Alluvium, 2013a; 2013b). In addition to this stationary component, the variable component of the EWDs represents two major passing flows in the WGWSS, viz.; the Wimmera River at Huddlestons Weir and Mt William Creek at Lake Lonsdale; both of which are a function of the upstream flow. That is, the amount passed in any given year is a proportion of the upstream flow at that site, up to a maximum flow rate. These passing flows are a result of the re-allocation of water savings arising from the replacement of the open channel distribution system with the Wimmera-Mallee Pipeline (DSE, 2011; GHD, 2011). Importantly, it is this variable component that has fundamentally changed the operating rules from a harvest-then-release regime, to one that passes a larger proportion of the system inflow for environmental purposes.

3.4.2 Optimisation engine

The motivation for using the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) for the optimisation engine was due to its wide acceptance by researchers as a baseline algorithm (Zitzler and Thiele, 1999; Van Veldhuizen and Lamont, 2000; Zitzler et al., 2001; Deb et al., 2002; Wu et al., 2010). The NSGA-II has properties that enable a population of solutions to converge towards the Pareto-optimal front and to maintain a good spread or diversity among the solutions (Deb et al., 2002). Figure 3.12 presents a flow chart of the NSGA-II showing one iteration, from time period t to $t+1$. Note that the green shaded arrow is used to show the direction of solution evolution and the blue shaded arrows are used to show the sorting of the solutions into the different non-dominated fronts.

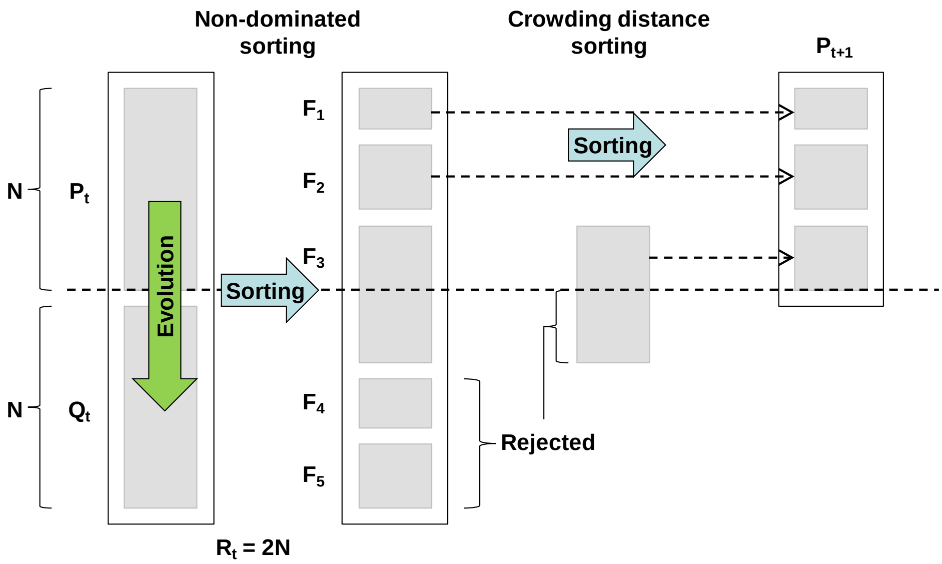


Figure 3.12 Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II)

For this thesis, the *parent* population (i.e. population P_t) is created by executing the REALM software package and by calculating the 18 performance metrics from the simulation of the Wimmera-Glenelg REALM model. The reader is referred to Section 3.2.4 for further details regarding the performance metrics for the WGWSS and to Section 3.4.1 for further details regarding the simulation engine of the O-S model. The *offspring* population (i.e. population Q_t) is created by using population P_t. This process of creating operating plans is explained in Sections 3.4.2.1.1 to 3.4.2.1.3 and is analogous to the evolutionary processes that exist in biology. These evolutionary processes are commonly referred to as *selection*, *crossover*, and *mutation* and are collectively referred to in this thesis as the *genetic operators*. Once these evolutionary processes are complete, a non-dominated sorting procedure is used to classify the entire population, $R_t = 2N$, using the dominance test as explained in Section 2.3 (refer to Equation 2.2). Once the non-dominated sorting is complete, the new population P_{t+1} is filled by operating plans of different non-dominated fronts, one at a time. The filling starts with the best non-dominated front (F_1) and continues with solutions of the second non-dominated front (F_2), followed by the third non-dominated front (F_3), and so on. Since the overall population size of R_t is $2N$, not all fronts may be accommodated in N slots available in the new population P_{t+1}. All fronts which could not be accommodated are simply deleted (i.e. F_4 and F_5). When the last front for filling P_{t+1} is considered (i.e. F_3), there may exist more operating plans in this front than the remaining slots in P_{t+1}. This is when a niching strategy is employed instead of arbitrarily discarding some operating plans from the last front. In the NSGA-II the operating plans that reside in the least crowded region in the last front are chosen to fill P_{t+1}. This niching ensures that a diverse set of operating plans is chosen from the last front. When the entire population converges to the Pareto front, the continuation of the NSGA-II will ensure a better diversity among the operating plans.

The NSGA-II niching strategy involves the calculation of the crowding distance (d). This involves estimating half of the perimeter of the maximum hypercube around a solution without including any other solution from the same front inside the hypercube (Deb, 2001). In Figure 3.13, the crowding distance of the i^{th} solution d_i in its front F (marked with the thick red dashed line) is the average side lengths of the cuboid (shown with the thin black dashed line).

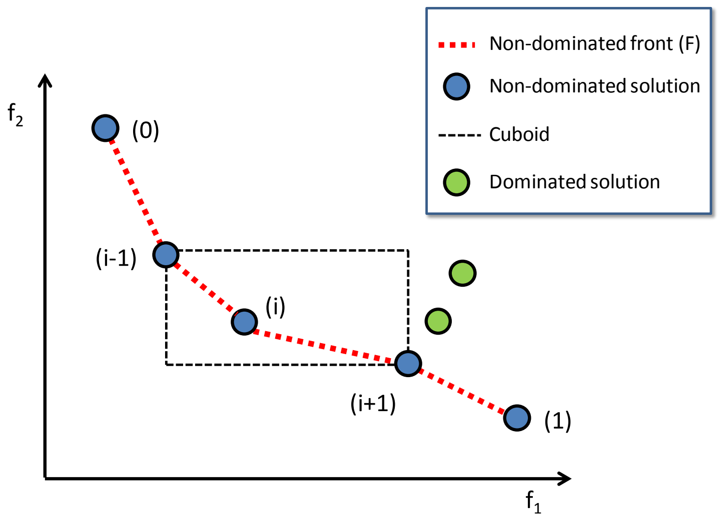


Figure 3.13 The crowding distance calculation used in NSGA-II

The three-step algorithm below is used to calculate d for each solution in front F. The index I_j denotes the solution index of the j^{th} member in the sorted list. For any objective, I_1 and I_l correspond to the lowest and the highest objective function values respectively.

Step 1: Call the number of solutions in front F as equal to $|F_1|$. For each solution i in front F, first assign $d_i = 0$.

Step 2: For each objective function $\mathrm{f_m}$, for which there are $\mathrm{m} = 1, 2, \ldots, \mathrm{M}$, sort the solutions from highest to lowest order of $\mathrm{f_m}$.

Step 3: For $\mathrm{m} = 1, 2, \ldots, \mathrm{M}$ assign a large distance to the boundary solutions (i.e. $\mathrm{d}_{\mathrm{I}_1}^{\mathrm{m}} = \mathrm{d}_{\mathrm{I}_l}^{\mathrm{m}} = \infty$, and for all other solutions $\mathrm{j} = 2$ to $(l - 1)$, assign d using Equation 3.66:

$$\mathrm{d}_{\mathrm{I}_{\mathrm{j+1}}}^{\mathrm{m}} = \mathrm{d}_{\mathrm{I}_{\mathrm{j}}}^{\mathrm{m}} + \frac{\mathrm{f}_{\mathrm{m}}^{(\mathrm{I}_{\mathrm{j+1}}^{\mathrm{m}})} - \mathrm{f}_{\mathrm{m}}^{(\mathrm{I}_{\mathrm{j-1}}^{\mathrm{m}})}}{\mathrm{f}_{\mathrm{m}}^{\max} - \mathrm{f}_{\mathrm{m}}^{\min}} \tag{3.66}$$

The second term of the right side of Equation 3.66 is the difference in objective function values between neighbouring solutions on either side of a particular solution. Thus, the crowding distance corresponds to half of the perimeter of the enclosing cuboid with the nearest neighbouring solutions placed on the vertices of the cuboid as shown in Figure 3.13 (i.e. the thin black dashed line). Therefore in this thesis, the greater the d value the more diversity that exists among the optimal operating plans along the Pareto front.

Sections 3.4.2.1 and 3.4.2.2 present the genetic operators (i.e. selection, crossover, and mutation) and the optimisation parameters (i.e. genetic operator settings, population size etc) respectively with due consideration to the factors which influenced the research methodology, as described in Section 3.1.

3.4.2.1 Genetic operators

For the purposes of describing the genetic operators, viz.; selection, crossover, and mutation, Sections 3.4.2.1.1 to 3.4.2.1.3 are described in terms of a sample higher order MOOP (referred to here as "the sample MOOP") concerning the operation of a water resource system with the following specifications:

- three objective functions that seek to minimise f_1, minimise f_2, and minimise f_3;
- four decision variables that represent different operating rules and which are collectively referred to as "the operating plan." These decision variables (i.e. dv_1, dv_2, dv_3, and dv_4) have values of either 1 or 0;
- population size, $\mathrm{N} = 6$ operating plans;
- probability of selection, $\mathrm{p_s} = 1$ (i.e. 6 out of 6 operating plans). This is explained further in Section 3.4.2.1.1;

- probability of crossover, $p_c = 0.33$ (i.e. 2 out of 6 operating plans). This is explained further in Section 3.4.2.1.2; and
- probability of mutation, $p_m = 0.17$ (i.e. 1 out of 6 operating plans). This is explained further in Section 3.4.2.1.3.

3.4.2.1.1 Selection

The primary aim of the selection operator is to make duplicates of good operating plans and eliminate bad operating plans from a population, while keeping the population size constant. According to Deb (2001), the most common methods are *tournament* selection, *proportionate* selection, and *ranking* selection. For the present study, the tournament selection is used as it has been shown that it has better or equivalent convergence and computational time complexity properties when compared to any other selection operator (Goldberg and Deb, 1991; Nicklow et al., 2010). In the tournament selection, tournaments are played between two solutions of a parent population (P_t) and the better operating plan is chosen and placed in the mating pool. Figure 3.14 shows the tournament selection process with respect to one objective function. In the case of the sample MOOP, the dominance test is applied to the three objective function values (i.e. f_1^n, f_2^n, and f_3^n) of the n^{th} operating plan to determine the better operating plan. Refer to Equation 2.2 for further details regarding the dominance test. Note that for ease of presentation, the green arrows which show the direction of evolution are shown pointing from left to right instead of from top to bottom as shown in Figure 3.12.

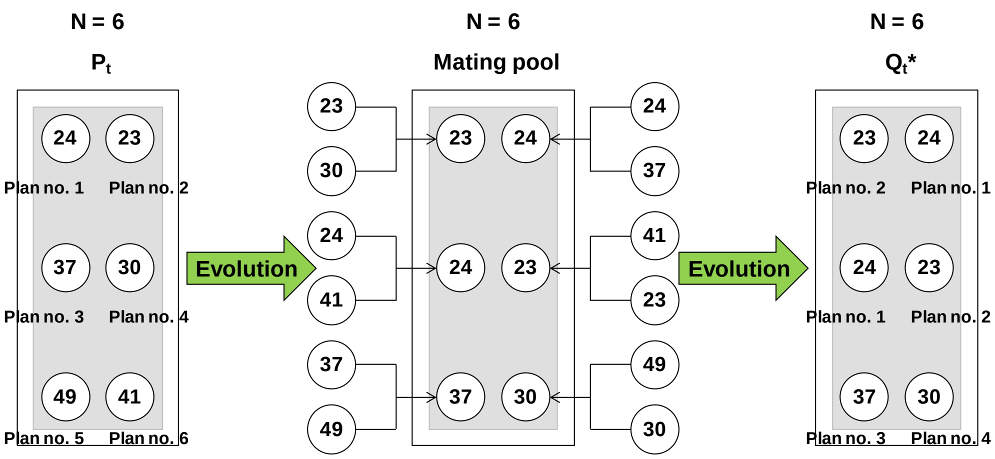


Figure 3.14 Tournament selection operator

Following the selection process for the first pair described earlier, two other operating plans are picked again (at random) and another slot in population Q_t* is filled with the better operating plan. As the probability of selection, $p_s = 1$, for the sample MOOP then $100p_c$% of operating plans in the population (i.e. all 6 operating plans) participate in the selection operation and $100(1 - p_c)$% of the population is simply copied to population Q_t*. In this case, each operating plan can be made to participate in exactly two tournaments. The best operating plan in a tournament will win two times, thereby making a copy of itself in population Q_t*, subject to the available slots in that population (i.e. Plan no. 1 and Plan no. 2 have been copied to population Q_t* whereas Plan no. 3 and Plan no. 4 did not have a spare slot in population Q_t* for their respective copies). Using a similar argument, the worst solution will lose in both tournaments and will be eliminated from the population (i.e. Plan no. 5 and Plan no. 6).

3.4.2.1.2 Crossover

Once all the slots in population Q_t* are filled, the crossover operator is applied to population Q_t*. Unlike the selection operator which is applied to the operating plans (i.e. Plan no. 1 to Plan no. 6), the crossover operator is applied to the decision variables (i.e. dv_1, dv_2, dv_3, and dv_4) of the operating plans in population Q_t*, assuming real-valued strings are used. Note that the creation of new operating plans in the population is performed by the crossover operator (and the mutation operator). There are a number of crossover operators, but in almost all crossover operators, two operating plans are picked from the population at random and some values of the decision variables are exchanged between operating plans to create new operating plans. As the probability of crossover, $p_c = 0.33$, for the sample MOOP then $100p_c$% of operating plans in population Q_t* (i.e. 2 operating plans) are randomly chosen to participate in the crossover operation and $100(1 - p_c)$% of operating plans in that population (i.e. remaining 4 operating plans) are simply copied to population Q_t**. Note that the crossover operator is mainly responsible for the search aspect of GAs, even though the mutation operator is also used for this purpose (Deb 2001). Figure 3.15 illustrates the *single-point* crossover operator for the sample MOOP. In terms of search power, Deb (2001) points out that the benefit of using the single-point crossover operator is that it preserves the structure of the (Q_t*) decision variables to the maximum extent possible in the newly formed operating plan in population Q_t**. For the sample MOOP, the crossover site is assumed to be between decision variables dv_1 and dv_2 (shown by the red dashed line). Once the crossover site is randomly selected, all decision variable values to the right of the crossover site (i.e. dv_2, dv_3 and dv_4) are exchanged between the two operating plans to create two new operating plans in population Q_t**.

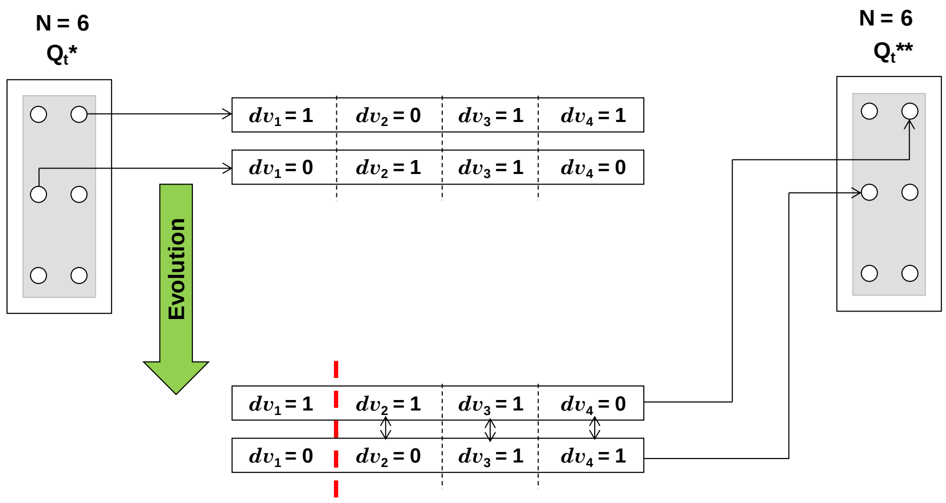


Figure 3.15 single-point crossover operator

3.4.2.1.3 Mutation

The mutation operator is required in the genetic process in order to maintain diversity in the population through the creation of new operating plans. Michalewicz (1992) states that the simplest mutation scheme would be to create an operating plan whose decision variable values have been selected at random (i.e. in this case, 1 or 0). As the probability of mutation, $p_m = 0.17$, for the sample MOOP then $100p_c$% of operating plans in population Q_t** (i.e. 1 operating plan) are randomly chosen to participate in the mutation operation and $100(1-p_c)$% of operating plans in that population (i.e. remaining 5 operating plans) are simply copied to population Q_t. Figure 3.16 shows the decision variable values for dv_1, dv_2, dv_3, and dv_4 which would be selected at random for one operating plan in population Q_t**. Note that the values selected at random for dv_2 and dv_3 in the newly formed (offspring) operating plan were coincidentally the same as their respective values in the (parent) operating plan.

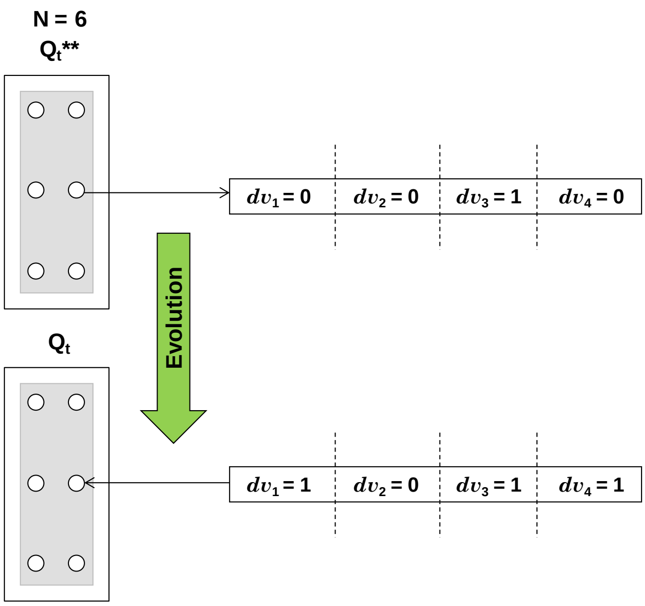


Figure 3.16 random mutation operator

Once mutation is complete, the NSGA-II undertakes the sorting procedure described in Section 3.4.1 to create population P_{t+1}.

3.4.2.2 <u>Optimisation parameters</u>

Once the genetic operators have been set up, another important challenge lies in specifying the parameters that control the search capabilities of the NSGA-II i.e. probability of selection (p_s), probability of crossover (p_c), probability of mutation (p_m), stopping criteria, and population size (N). The parameter settings for the O-S model were based on the outcomes of separate studies and confirmed with sensitivity runs using the O-S model. These outcomes are discussed here together with the analysis of six O-S model runs which show the sensitivity of different optimisation parameter settings in terms of the diversity of optimal operating plans along the Pareto front. Importantly, the diversity of operating plans is considered to be an important attribute (in practice) given that it influences the range of different optimal operating plans that are available for selection by the DM. A greater level of diversity means that the DM has an increased range of operating plans available for the purposes of achieving desired levels of sustainability for water resources systems.

In addition to choosing an appropriate population size, a MOOP also requires a balanced approach between exploitation and exploration of solutions (Deb 2001). As explained earlier in Section 3.4.2.1.1, the selection operator is responsible for exploiting the population in order to make duplicates of good operating plans and eliminating bad ones. The exploration process is caused by the crossover and mutation operators discussed in Sections 3.4.2.1.2 and 3.4.2.1.3 respectively. In cases where the $\mathrm{p_s}$ is set too high, the optimisation engine will tend to make too many copies of the best operating plans and cause the population to lose its diversity very quickly. Such a situation would cause the population to become victim of excessive selection pressure and tend to converge to a set of sub-optimal operating plans. Given that all the GA studies referred to in this thesis do not specify the $\mathrm{p_s}$ value, it is assumed that all members of the population participate in the selection process (i.e. $\mathrm{p_s} = 1$). To restore the balance and re-introduce the diversity into the population, the $\mathrm{p_c}$ and $\mathrm{p_m}$ settings would also need to be high in order to create (offspring) operating plans which are quite different from the (parent) operating plans. In other cases where the selection pressure is quite low, the GA would require a large number of iterations to navigate its search towards the Pareto front. Deb and Agrawal (1999) investigated different GA operator and parameter settings and applied these to problems of varying difficulty. The outcomes of their study showed:

- Simple MOOPs (e.g. unimodel and linear problems) are best solved using the three genetic operators with a smaller population size. Deb and Agrawal (1999) referred to these optimisation parameter settings as *selecto-mutation GAs*. An alternative parameter setting which does not include the mutation operator also works with these problems, however the population size requirement tends to be higher than that required for the first mentioned optimisation parameter settings. However, it is worth highlighting that Deb and Agrawal (1999) concluded from their study that the selecto-mutation GAs were often not successful in finding the Pareto front.
- Complex MOOPs (e.g. multimodal and higher order problems) are best solved with optimisation parameter settings that have little or no $\mathrm{p_m}$value. Deb and Agrawal (1999) referred to these optimisation parameter settings as *selecto-recombinative GAs.* As the exploration pressure offered by these parameter settings is reduced given the low $\mathrm{p_m}$values, the population size requirement tends to be higher.

3.4.2.2.1 Sensitivity analysis

Whilst the higher order MOOP for the WGWSS has already been presented in Section 3.3, the problem is briefly described again for the reader's convenience and for completeness of Section 3.4.2.2. The problem is to optimise the system operating rules for the WGWSS with regards to 18 competing objectives which consider environmental, social, consumptive, and system-wide interests for water - refer to Equations 3.21 to 3.38 in Section 3.3.1. As explained in Section 3.3, the problem is formulated based on the assumption that the sustainability of the WGWSS is measured in terms of three performance metrics (i.e. reliability, resiliency, and vulnerability) concerning the above four interests for water.

For the purposes of investigating the sensitivity of different parameter settings in terms of the diversity of optimal operating plans along the Pareto front, six O-S model runs are formulated based on the outcomes of Deb and Agrawal (1999), as described in Section 3.4.2.2. Additionally, to investigate the effect of population size on the diversity of optimal operating plans, the O-S model runs are formulated with two population sizes (i.e. $N = 30$ and $N = 100$), representing small and large population sizes respectively. Table 3.9 summarises these O-S model runs in three sets, corresponding to their different parameter settings (i.e. selecto-mutation GAs, neither selecto-mutation GAs nor selecto-recombinative GAs, and selecto-recombinative GAs)

Table 3.9 Six O-S model runs used in sensitivity analysis

Optimisation operator	Optimisation-simulation scenarios (**bold**) and corresponding optimisation parameter settings					
	Run (sm30)	**Run (sm100)**	**Run (n30)**	**Run (n100)**	**Run (sr30)**	**Run (sr100)**
Probability of crossover (p_c)	0.2	0.2	0.5	0.5	0.8	0.8
Probability of mutation (p_m)	0.8	0.8	0.5	0.5	0.2	0.2
Population size (N)	30	100	30	100	30	100

The following notation is used to describe the three sets of O-S model runs:

- selecto-<u>m</u>utation GAs with $N = \underline{30}$ and $N = \underline{100}$, referred to as "Run (sm30)" and "Run (sm100)" respectively;

- neither selecto-mutation GAs nor selecto-recombinative GAs with $\mathrm{N} = \underline{30}$ and $\mathrm{N} = \underline{100}$, referred to as “Run (n30)” and “Run (n100)” respectively; and
- selecto-recombinative GAs with $\mathrm{N} = \underline{30}$ and $\mathrm{N} = \underline{100}$, referred to as “Run (sr30)” and “Run (sr100)” respectively.

The diversity of the optimal operating plans found by the O-S model in each case is measured in terms of the crowding distance (d) as calculated by the NSGA-II (refer Section 3.4.2). For the purposes of this sensitivity analysis, the optimal operating plans at the fifth generation are selected for analysis for reasons of the slow convergence to the Pareto front as described in Section 3.1. Table 3.10 summarises the modelling results for the six O-S modelling runs in terms of the mean of the crowding distances (d) for the optimal operating plans.

Table 3.10 Mean crowding distance (d) of the optimal operating plans for a range of p_c and p_m values assuming population sizes $\mathrm{N} = 30$ and $\mathrm{N} = 100$

Generation (t)	Mean of crowding distances (d) for optimal operating plans					
	Run (sm30)	Run (sm100)	Run (n30)	Run (n100)	Run (sr30)	Run (sr100)
	$P_c = 0.2$		$P_c = 0.5$		$P_c = 0.8$	
	$P_m = 0.8$		$P_m = 0.5$		$P_m = 0.2$	
	N = 30	N = 100	N = 30	N = 100	N = 30	N = 100
1	3.095	1.148	3.764	1.305	4.832	1.293
2	3.834	1.188	3.582	1.054	3.954	1.311
3	3.450	1.134	3.999	1.148	4.600	1.329
4	3.651	1.096	4.872	1.249	4.592	1.046
5	3.642	1.175	5.027	1.223	4.272	1.210
Mean	3.534	1.148	4.249	1.196	4.450	1.238

‘d’ refers to the crowding distance of an operating plan with respect to all 18 objective functions as described in Section 3.4.2
‘P_c’ refers to the probability of crossover as described in Section 3.4.2.1.2
‘P_m’ refers to the probability of mutation as described in Section 3.4.2.1.3

The following is a summary of the observations made from the O-S modelling results presented in Table 3.10 in terms of the overall mean crowding distances (i.e. over the 5 generations):

- Runs that used a population size of $\mathrm{N} = 30$ found operating plans that were more diverse than those runs that used a population size of $\mathrm{N} = 100$. This result is to be expected as the distance between operating plans in the smaller population would need to be larger in order to cover the same area along the

Pareto front, assuming that the same area is achieved under both population sizes.

- The selecto-recombinative GAs found the most diverse operating plans, irrespective of the population size.

Therefore, based on these O-S modelling results the following selecto-recombinative parameter settings are used throughout this thesis:

- $p_s = 1,\ p_c = 0.8,\ p_m = 0.2, N = 100$

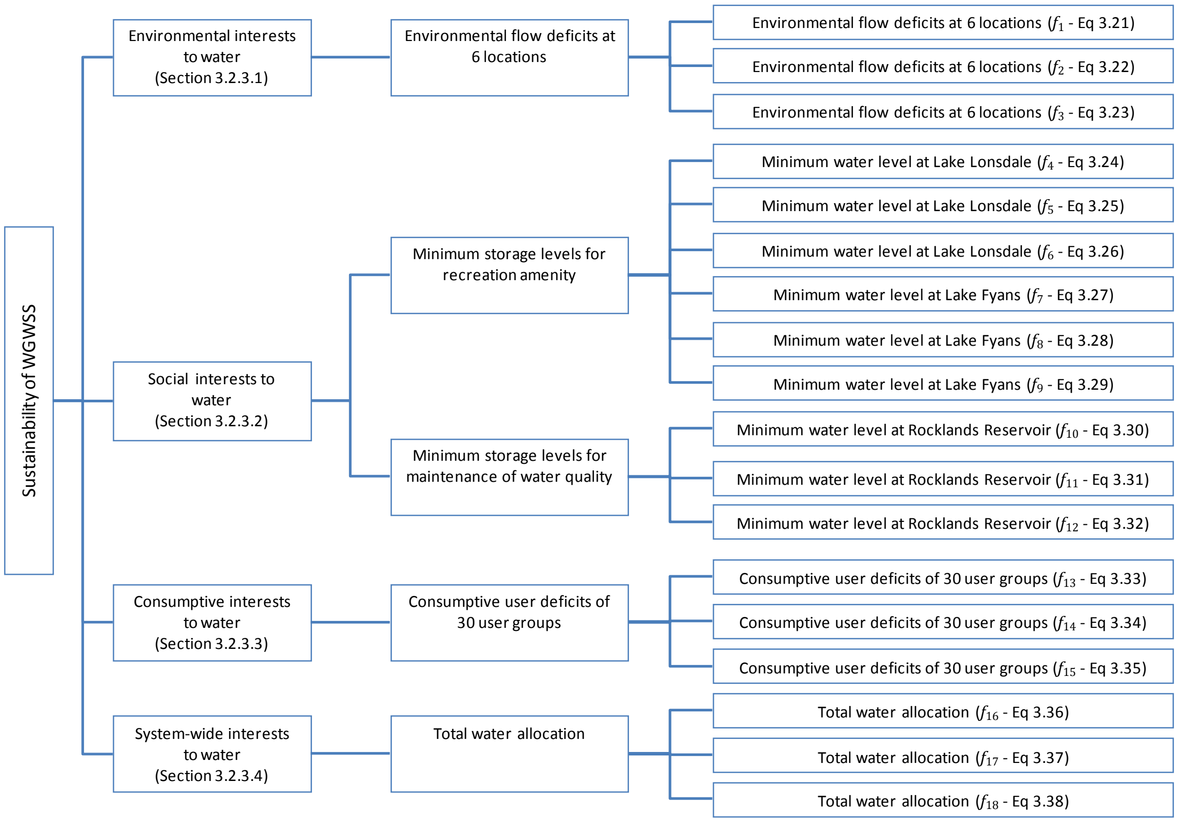
3.5 Sustainability Indices for the Wimmera-Glenelg Water Supply System

In their study of sustainability criteria for water resource systems, Loucks and Gladwell (1999) devised an index which could be used to compare the sustainability of one water management policy to another. Their index measured the performance of water resource systems over time with respect to the relevant criteria for that system. For the purposes of this thesis, the index would need to represent a range of stakeholders' whose varied interests collectively underpin the sustainability of the WGWSS. In a sense the index would need to be conducive to the preservation of the shared vision for the operation of the water resource system. Such an index is referred to in this thesis as a *sustainability index*.

Belton and Stewart (2002) refer to the following often quoted statement with respect to the structuring of multi-criteria decision making problems:

"*A problem well structured is a problem half solved*"

As explained in Section 3.3, the higher order MOOP was structured with the sustainability of the WGWSS as an overall goal and so it makes for a logical basis on which to develop a sustainability index. For the reader's convenience, the value tree that was used to structure the higher order MOOP for the WGWSS is shown again in Figure 3.17. Note that this is the same value tree shown in Figure 3.4. For ease of presentation, the top of the tree is shown to the left of the figure and corresponds to the highest level criteria, being the sustainability of the WGWSS. The next criteria level down represents the four interests for water identified (i.e. environmental, social, consumptive, and system-wide interests). The third criteria level from the top represents a further breakdown from the four interests for water of the second level, and the lowest level criteria represent the 18 conflicting objective functions, f_1 to f_{18} (refer to Equations 3.21 to 3.38).



Note: 'f_m' refers to the m^{th} objective function which is defined in Section 3.3.1

Figure 3.17 Value tree of the higher order MOOP for the WGWSS

3.5.1 The Sustainability Index

Figure 3.18 shows the Sustainability Index (referred to here as "the SI") which has been developed using the value tree of the higher order MOOP for the WGWSS (Figure 3.17). From top to bottom, there are four levels that constitute the SI which are referred to in this thesis as the *index*, *component*, *indicator*, and *sub-indicator* levels.

As the index represents an aggregation of the three lower levels, it makes sense to describe the four levels of the SI starting at the lowest level and aggregating upwards towards the SI itself.

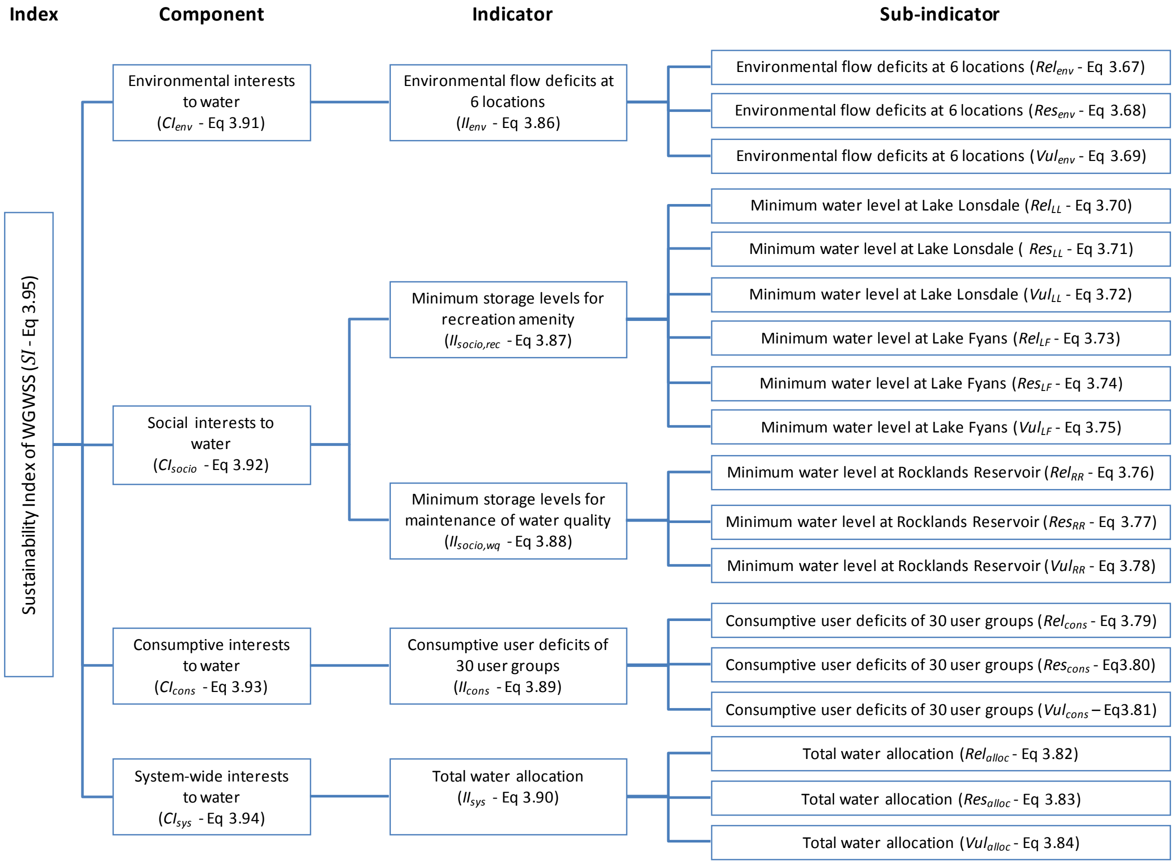


Figure 3.18 The Sustainability Index (SI) for the WGWSS

The lowest level of the SI is referred to as the *sub-indicator level* which consists of the 18 performance metrics presented in Section 3.2.4 (refer to Equations 3.3 to 3.20). For the reader's convenience and for completeness of the remaining sections under Section 3.5, these performance metrics are summarised in Equations 3.67 to 3.84. Note that Equations 3.67 to 3.84 are the same as Equations 3.3 to 3.20. The higher order MOOP is formulated based on the assumption that the sustainability of the WGWSS is measured in terms of three performance metrics (i.e. reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i)) for the i^{th} interest for water. Equations 3.67 to 3.69 relate to three environmental (env) interests for water expressed in terms of nil environmental flow deficits. Equations 3.70 to 3.78 relate to nine social ($socio$)

interests for water expressed in terms of the volume of the j^{th} storage (S_j) being Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR). Equations 3.79 to 3.81 relate to three consumptive ($cons$) interests for water expressed in terms of nil supply deficits. Equations 3.82 to 3.84 relate to three system-wide interests for water expressed in terms of water allocations ($alloc$). These sub-indicators are particularly important in terms of providing the link between the interests for water in the WGWSS and the search for candidate optimal operating plans. Thus, the search for candidate optimal operating plans is relevant to the problem at hand; a desire to develop optimal operating plans for the WGWSS that have sustainability as an overall goal.

$$Rel_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0}{n} \text{, where } n = 118 \text{ years} \tag{3.67}$$

$$Res_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{env,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occured}} \tag{3.68}$$

$$Vul_{env} = \frac{(\sum_{t=1}^{12} Def_{env,t}) / \text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{env,t})} \tag{3.69}$$

$$Rel_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.70}$$

$$Res_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML follows } S_{LL,t} \leq 5{,}379 \text{ ML}}{\text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occured}} \tag{3.71}$$

$$Vul_{LL} = \frac{(\sum[\max\{0, (5{,}379 \text{ ML} - S_{LL,t})\}] / \text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occurred}}{\text{Average of } S_{LL,t}} \tag{3.72}$$

$$Rel_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.73}$$

$$Res_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML follows } S_{LF,t} \leq 1{,}761 \text{ ML}}{\text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occured}} \tag{3.74}$$

$$Vul_{LF} \quad \frac{(\sum[\max\{0, (1{,}761 \text{ ML} - S_{LF,t})\}] / \text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occurred}}{\text{Average of } S_{LF,t}} \tag{3.75}$$

$$Rel_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML}}{n} \text{, where } n = 1{,}416 \text{ months} \tag{3.76}$$

$$Res_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML follows } S_{RR,t} \leq 69{,}600 \text{ ML}}{\text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occured}} \tag{3.77}$$

$$Vul_{RR} = \frac{(\sum[\max\{0, (69{,}600 \text{ ML} - S_{RR,t})\}] / \text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occurred}}{\text{Average of } S_{RR,t}} \tag{3.78}$$

$$Rel_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0}{n} \text{, where } n = 118 \text{ years} \tag{3.79}$$

$$Res_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{cons,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occured}} \tag{3.80}$$

$$Vul_{cons} = \frac{(\sum_{t=1}^{12} Def_{cons,t}) / \text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{cons,t})} \tag{3.81}$$

$$Rel_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML}}{n} \text{, where } n = 118 \text{ years} \tag{3.82}$$

$$Res_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML follows } W_{system,June} < 97{,}550 \text{ ML}}{\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}} \tag{3.83}$$

$$Vul_{alloc} = \frac{(\sum(97{,}550 \text{ ML} - W_{system,June}) / \text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}}{\text{Average of } W_{system,June}} \tag{3.84}$$

Where, $t = \text{July, August, September, } \ldots\ldots, \text{June;}$

The next level up from the lowest is referred to as the *indicator level* which represents an aggregation of the sub-indicators given in Equations 3.67 to 3.84. Before these indicators are presented it is necessary to present the multiplicative aggregation scheme which has been adopted for this thesis. This aggregation scheme is based on the sustainability index (SI_i) developed by Sandoval-Solis et al. (2011) which is expressed as the geometric average of M performance metrics for the i^{th} water user as given by Equation 3.85. Note that the reasons for adopting this aggregation scheme are explained later this section.

$$\mathrm{SI}_i = \left[\prod_{m=1}^{M} P_m^i\right]^{1/M} \tag{3.85}$$

Where,

$0 \leq \mathrm{SI}_i \leq 1$ (note: 0 is the lowest and 1 is the highest level of sustainability for the i^{th} water user)

m refers to performance metric, $m = 1$ to M

P_m^i refers to the m^{th} performance metric for the i^{th} water user

Thus, the *Indicator-level Index* for the i^{th} interest for water (II_i) are as follows:

$$II_{env} = [Rel_{env} \times Res_{env} \times (1 - Vul_{env})]^{1/3} \tag{3.86}$$

$$II_{socio,rec} = [Rel_{LL} \times Res_{LL} \times (1 - Vul_{LL}) \times Rel_{LF} \times Res_{LF} \times (1 - Vul_{LF})]^{1/6} \tag{3.87}$$

$$II_{socio,wq} = [Rel_{RR} \times Res_{RR} \times (1 - Vul_{RR})]^{1/3} \tag{3.88}$$

$$II_{cons} = [Rel_{cons} \times Res_{cons} \times (1 - Vul_{cons})]^{1/3} \tag{3.89}$$

$$II_{sys} = [Rel_{alloc} \times Res_{alloc} \times (1 - Vul_{alloc})]^{1/3} \tag{3.90}$$

The next level up from the second-lowest is referred to as the *component level* which represents a multiplicative aggregation of the indicators given in Equations 3.86 to 3.90. Thus, the *Component-level Index* for the i^{th} interest for water (CI_i) are as follows:

$$CI_{env} = II_{env} \tag{3.91}$$

$$CI_{socio} = \left[(II_{socio,rec})^6 \times (II_{socio,wq})^3\right]^{1/9} \tag{3.92}$$

$$CI_{cons} = II_{cons} \tag{3.93}$$

$$CI_{sys} = II_{sys} \tag{3.94}$$

Finally, the sustainability of the WGWSS (SI) represents a multiplicative aggregation of the components given in Equations 3.91 to 3.94 as follows:

$$SI = \left[(CI_{env})^3 \times (CI_{socio})^9 \times (CI_{cons})^3 \times (CI_{sys})^3\right]^{1/18} \tag{3.95}$$

The motivation for using a multiplicative aggregation scheme for the SI originates from studies by Loucks (1997), Loucks and Gladwell (1999), and Sandoval-Solis et al. (2011) in which a sustainability index was proposed for water resources planning and management. The authors of these studies used performance metrics to evaluate water management policies and to enable the comparison of alternative policies. One of the key attractions to their sustainability index was that it could be used to summarise the performance of alternative policies from the perspective of different water users. In the context of this thesis, this attribute of the sustainability index is particularly beneficial as it can be used to explicitly account for all the major interests for water in the higher order MOOP for the WGWSS.

Note that whilst Equations 3.86 to 3.95 use the same multiplicative aggregation scheme as that used in Equation 3.85, the SI for this thesis refers to the sustainability of the WGWSS in terms of all interests for water collectively as distinct from the single water user referred to in the SI_i (i.e. Equation 3.85). In which case, the SI may be thought of as an extension of the aforementioned studies as applied to higher order MOOPs that concern a range of interests for water. Moreover, Section 3.5.2 goes further to demonstrate the use of a weighted SI as part of a process of selecting a preferred optimal operating plan from the Pareto front.

The following are the main benefits of developing the SI based on the work by Loucks (1997), Loucks and Gladwell (1999), and Sandoval-Solis et al. (2011):

- Given that the performance metrics must have a value of between 0 and 1 means that the SI_i has the flexibility to include a wide range of interests for water whose competing needs may not necessarily be commensurate. Moreover, the various interests for water may elect to express their SI_i in terms of any number of performance metrics. For instance, the social interests for water in the WGWSS have 9 performance metrics (i.e. Equations 3.68 to 3.76) compared to the 3 performance metrics for each of the other interests for water.

- The three performance metrics as described in Section 3.2.4 (i.e. reliability, resiliency, and vulnerability) summarise essential performance parameters in a meaningful manner rather than simply adding broad disparate factors. This is confirmed by the use of the SI_i in the scientific community as cited by Sandoval-Solis et al. (2011). Moreover, McMahon et al. (2006) goes further to state that the SI_i is the only quantitive measure of sustainability for water resources systems as it combines the three performance metrics into one index.
- The SI_i proposed by Sandoval-Solis et al. (2011) uses the geometric average of the three performance metrics providing better scaling characteristics than the arithmetic average. For instance, a water user whose reliability, resiliency, and vulnerability is 0.5 for each performance metric has an arithmetic average of $\frac{0.5+0.5+0.5}{3} = 0.5$ and a geometric average of $(0.5 \times 0.5 \times 0.5)^{1/3} = 0.5$. However, a water user whose reliability is 0.9, resiliency is 0.9, and vulnerability is 0 has an arithmetic average of 0.6 and a geometric average of 0. Thus, the scaling of the SI_i does not obscure poor performance as does the arithmetic average. In the context of this thesis, such scaling characteristics would assist the DM in reaching consensus amongst competing interests for water by favouring optimal operating plans that have *good* values for all metrics. It is worth highlighting that in cases where the DM has a particular interest in individual metrics (as opposed to all metrics in the SI), the geometric average may tend to penalise optimal operating plans that have considerable variability in that metric of interest.

3.5.2 The Weighted Sustainability Index

The process of selecting a preferred optimal operating plan from the Pareto front brings together two aspects of multi-objective optimisation, namely; (i) the quantitative information regarding the characteristics of the optimal operating plans along the Pareto front; and (ii) the higher level qualitative information in the form of stakeholders' preferences. With reference to the literature on multi-objective optimisation, the quantitative information relating to the optimal operating plans is analysed in terms of the objective space and the decision space. As explained in Section 3.5.1, this thesis proposes that the SI be used as the means to evaluate and compare optimal operating plans in both the objective space and the decision space. With respect to the higher level qualitative information, it is necessary to develop a conceptual model which represents stakeholders' preferences and value judgements. Methods available under the umbrella term multi-criteria decision analysis (MCDA) are widely used for the purpose of facilitating the exploration of decisions that take explicit account of multiple factors or criteria (Belton and Stewart, 2002). As explained in Section 2.3.3, there are three broad classes of preference models adopted in multi-criteria decision problems as follows:

- *Value measurement models* associate a real number with each solution (or in this case optimal operating plan) in order to produce a preference order on the solutions consistent with the DM's value judgements.
- *Goal, aspiration or reference level models* set out to establish desirable or satisfactory levels of achievement for each criterion and then to find optimal operating plans which are in some sense closest to achieving these desirable goals or aspirations.
- *Outranking models* undertake a pair-wise comparison of optimal operating plans to determine the extent to which a preference for one optimal operating plan compares to another plan. These models set out to establish the strength of evidence favouring the preference of one optimal plan over another.

The use of the SI (in evaluating and comparing optimal operating plans) lends itself to the value measurement preference model. This is due to the SI providing (i) a means of associating a real number for each optimal operating plan; and (ii) an ordering or ranking of these plans, where SI values of 0 and 1 represent the lowest and highest levels of sustainability in the WGWSS respectively.

Belton and Stewart (2002) explain that the aforementioned preference models contain two primary components, namely:

- a set of weights which define the relative importance or desirability of achieving different levels of performance for each criterion; and
- an aggregation scheme which allows inter-criteria comparisons or trade-offs in order to combine preferences across criteria.

The SI presented in Section 3.5.1 provides the basis for these two primary components by allowing for the inclusion of (i) the j^{th} stakeholder's weight for the m^{th} performance metric (w_m^j); and (ii) a weighted (geometric average) multiplicative aggregation scheme. Thus, the Weighted Sustainability Index (SI^j) for the j^{th} stakeholder is expressed as follows:

$$SI^j = \left[\prod_{m=1}^{M} {P_m^j}^{w_m^j}\right]^{1/(\sum_{m=1}^{M} w_m^j)} \quad (3.96)$$

Where,

$0 \leq SI^j \leq 1$ (note: 0 is the lowest and 1 is the highest level of sustainability for the j^{th} stakeholder)

m refers to performance metric, $m = 1$ to M

P_m^j refers to the j^{th} stakeholder's m^{th} performance metric

w_m^j refers to the j^{th} stakeholder's weight for the m^{th} performance metric

The SI^j has all the benefits of the SI in terms of flexibility and scalability as mentioned in Section 3.5.1 and provides continuity in the multi-criterial decision-making process i.e. from evaluation and comparison of optimal operating plans through to the selection of a preferred optimal operating plan. Figure 3.19 summarises the j^{th} stakeholder's Weighted Component-level Index for the i^{th} interest for water (CI_i^j) and the Weighted Sustainability Index (SI^j) for the WGWSS.

It is important to highlight the following reasons for using the j^{th} stakeholder's weights at the sub-indicator level for the CI_i^j and the SI^j:

- the weights at the sub-indicator level represent the least amount of subjectivity (compared to all other levels of the SI^j) given that these are not aggregates of lower levels of the SI^j. This means that the selection of a preferred optimal operating plan is affected by the least amount of bias that may exist amongst stakeholders compared to other levels of the SI^j; and

- subjectivity (through the use of weights) is introduced *a posteriori* (post-optimisation) and so weights may be revised without having to necessarily repeat the optimisation process. This may lead to a reduction in the computational effort involved in the search for and selection of optimal operating plans during the process of stakeholder negotiations.

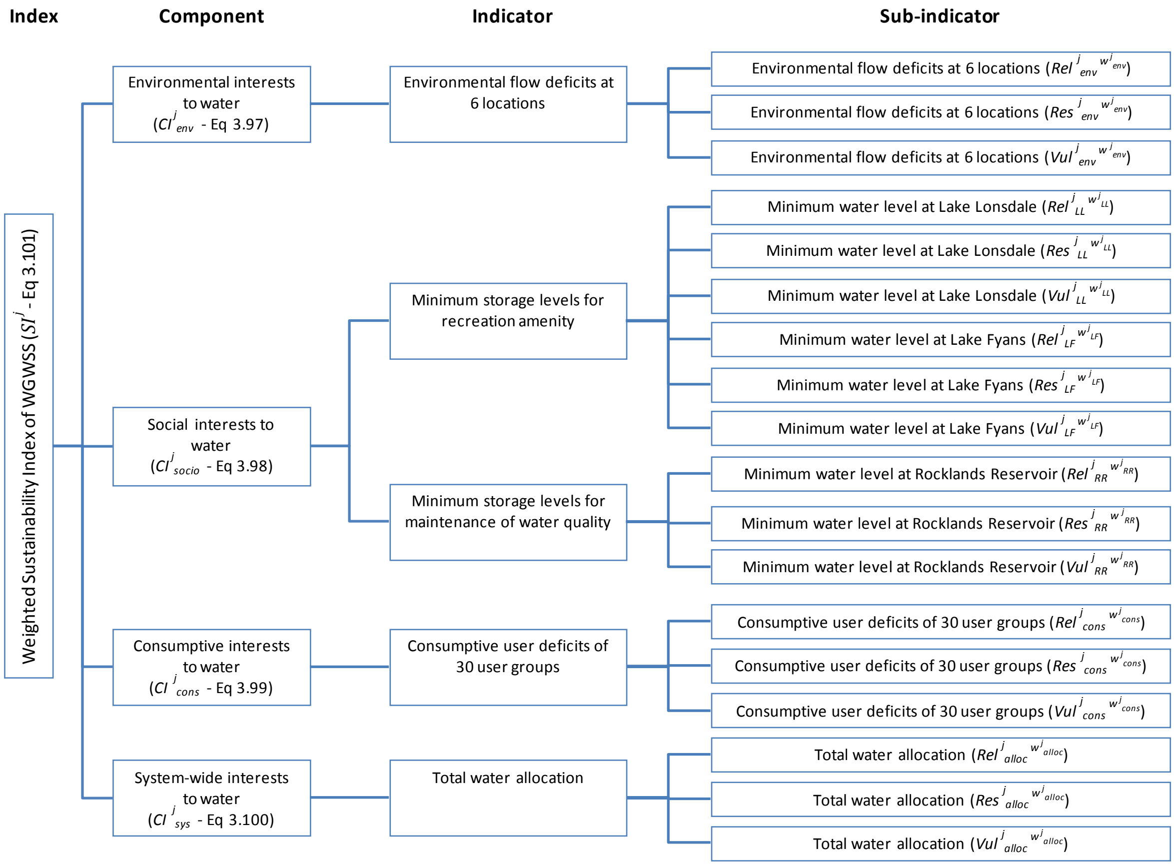


Figure 3.19 The j^{th} stakeholder's Weighted Sustainability Index (SI^j) for the WGWSS

Modifying Equations 3.91 to 3.95 in line with Equation 3.96 gives the j^{th} stakeholder's Weighted Component-level Index for the i^{th} interest for water (CI_i^j) and the Weighted Sustainability Index (SI^j) for the WGWSS as follows:

$$CI_{env}^{j} = \left[(Rel_{env})^{w_1^j} \times (Res_{env})^{w_2^j} \times (1 - Vul_{env})^{w_3^j}\right]^{1/(\sum_{m=1}^{3} w_m^j)} \quad (3.97)$$

$$CI_{socio}^{j} = [(Rel_{LL})^{w_4^j} \times (Res_{LL})^{w_5^j} \times (1 - Vul_{LL})^{w_6^j} \times (Rel_{LF})^{w_7^j} \times (Res_{LF})^{w_8^j} \times (1 - Vul_{LF})^{w_9^j} \times (Rel_{RR})^{w_{10}^j} \times (Res_{RR})^{w_{11}^j} \times (1 - Vul_{RR})^{w_{12}^j}]^{1/(\sum_{m=4}^{12} w_m^j)} \quad (3.98)$$

$$CI_{cons}^{j} = \left[(Rel_{cons})^{w_{13}^j} \times (Res_{cons})^{w_{14}^j} \times (1 - Vul_{cons})^{w_{15}^j}\right]^{1/(\sum_{m=13}^{15} w_m^j)} \quad (3.99)$$

$$CI_{sys}^{j} = \left[(Rel_{alloc})^{w_{16}^j} \times (Res_{alloc})^{w_{17}^j} \times (1 - Vul_{alloc})^{w_{18}^j}\right]^{1/(\sum_{m=16}^{18} w_m^j)} \quad (3.100)$$

$$SI^{j} = \left[(CI_{env}^{j})^{1/(\sum_{m=1}^{3} w_m^j)} \times (CI_{socio}^{j})^{1/(\sum_{m=4}^{12} w_m^j)} \times (CI_{cons}^{j})^{1/(\sum_{m=13}^{15} w_m^j)} \times (CI_{sys}^{j})^{1/(\sum_{m=16}^{18} w_m^j)}\right]^{1/(\sum_{m=1}^{18} w_m^j)} \quad (3.101)$$

Where,

w_m^j, refers to the j^{th} stakeholder's weights for the m^{th} performance metric

Note that mathematically, the weighted geometric average with equal weights is the same as the geometric average (i.e. $SI^j = SI$ and $CI_i^j = CI_i$).

3.6 Summary

Chapter 3 presented a structured multi-objective optimisation procedure which was aimed at assisting the decision maker (DM) to develop a shared vision for the operation of complex water resource systems considering climate change. This involved (i) the identification of all the major interests for water in a complex water resource system; (ii) the formulation of a MOOP that takes explicit account of all the major interests for water in the system; (iii) the setting up of the O-S model used to solve for this MOOP; and (iv) the specification of indices used to analyse and rank optimal solutions. This structured procedure was applied to a MOOP for the WGWSS with a view to developing optimal operating plans that have sustainability as an overall goal.

Section 3.2 described the WGWSS in terms of the physical network including the 12 headwork storages, the interconnecting open channels and pipelines, and the water demands. A brief introduction was provided of the trusted simulation model that was used as part of the O-S model setup given its use in major water resource planning studies in the Wimmera-Glenelg region. This brief introduction of the so called “Wimmera-Glenelg REALM model” provided the necessary means for describing the various interests for water in the WGWSS. These interests for water were broadly categorised into those which represented environmental (env); social ($socio$) i.e. recreation at Lake Lonsdale (LL) and at Lake Fyans (LF), and for water quality at Rocklands Reservoir (RR); consumptive ($cons$); and those that affected all users system-wide in terms of water allocations ($alloc$). In each case, the process of identifying the four interests for water involved developing an understanding of the model configuration for that particular user together with any relevant criteria by which to evaluate candidate optimal operating plans. For instance in the case of the environmental interests for water, flow requirements were configured in the Wimmera-Glenelg REALM model as separate EWDs in order to provide for the required flows in the various stream reaches. In which case, the criterion that was used to evaluate candidate optimal operating plans with respect to EWDs was the difference between the amount that was required at a particular location (i.e. demand) and the amount that was provided to that location (i.e. supply). Such criteria together with three broad performance metrics for the i^{th} interest for water, being reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i), served as the basis for the objective functions used in the formulation of the MOOP. A total of 18 performance metrics were used to evaluate candidate optimal operating plans on a quantitative basis with respect to the four interests for water identified viz. environmental (i.e. Rel_{env}, Res_{env}, and Vul_{env}), social (i.e. Rel_{LL}, Res_{LL}, Vul_{LL}, Rel_{LF}, Res_{LF}, Vul_{LF}, Rel_{RR}, Res_{RR}, and Vul_{RR}), consumptive (i.e. Rel_{cons}, Res_{cons}, and Vul_{cons}), and the system-wide interests (i.e. Rel_{alloc}, Res_{alloc}, and Vul_{alloc}).

Section 3.3 presented the formulation of the higher order MOOP in terms of a hierarchical structure for which the sustainability of the WGWSS was assumed to represent the highest level criteria. The second level of the problem hierarchy represented the four major interests for water (i.e. environmental, social, consumptive, and system-wide interests) and the lowest level criteria represented the 18 objective functions for the MOOP. Structuring the higher order MOOP in this way provided the necessary means for (i) taking explicit account of all the major interests for water in the WGWSS; and (ii) the evaluation of candidate optimal operating plans. It was also explained that formulating a higher order MOOP using higher criteria levels (e.g. the four interests for water) would have the effect of reducing the dimensionality of the problem whereas lower criteria levels (e.g. the 18 objective functions) would have the reverse effect. It was explained that the objective functions of a MOOP play a role of guiding the optimisation search towards candidate optimal operating plans that perform the best in terms of the values of these objective functions. The 18 objective functions of the higher order MOOP were formulated using the aforementioned 18 performance metrics. Thus, the sustainability of the WGWSS was measured in terms of maximising the reliability (Rel_i), maximising the resiliency (Res_i), and minimising the vulnerability (Vul_i) of the i^{th} interest for water. The decision variables for the higher order MOOP were expressed in terms of 24 water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. The mathematical equations for the 24 decision variables were presented in terms of the six areas of system operation viz. (i) priorities of supply (i.e. dv_1 to dv_7); (ii) a storage flood reserve volume (i.e. dv_8); (iii) environmental allocation shares (i.e. dv_9 to dv_{11}); (iv) flow paths (i.e. dv_{12} and dv_{13}); (v) storage maximum operating volumes (i.e. dv_{14} to dv_{20}); and (vi) storage draw down priorities and storage targets (i.e. dv_{21} to dv_{24}). These planning decisions were collectively referred to as an "operating plan." The constraints of the problem were specified both in terms of the formulation of the MOOP (i.e. as bounds on variables and as integer constraints) and also in terms of the real-world limitations of the WGWSS (i.e. as statutory constraints and as physical constraints). By far, most of the problem constraints were already configured in the Wimmera-Glenelg REALM model. It was explained that this was one of the major benefits of using an O-S modelling approach in that many of the complexities of a real-world water resource system were already configured in existing well trusted simulation models.

Section 3.4 described the setup of the O-S model that was used to solve the higher order MOOP in Section 3.3. An overview of the O-S modelling procedure was provided starting from the initial population of randomly generated operating plans through to the final population of optimal operating plans. As the initial population required the execution of the Wimmera-Glenelg REALM model, the setup of the simulation engine was presented in the first instance, in terms of the system file and data inputs. It was explained that the original simulation model, known as the WMPP2104.sys file, was replaced by a surrogate model in order to (i) improve its flexibility and stability in terms of changing from one set of operating rules to another; and (ii) exchange information between it and the optimisation engine so that the O-S model could successfully iterate to the population of optimal operating plans. This lower-fidelity physically based surrogate model was referred to as the "Wimmera-Glenelg REALM model" and showed a good fit with the WMPP2104.sys file (i.e. Nash-Sutcliffe efficiency index, $E_f = 0.94$).

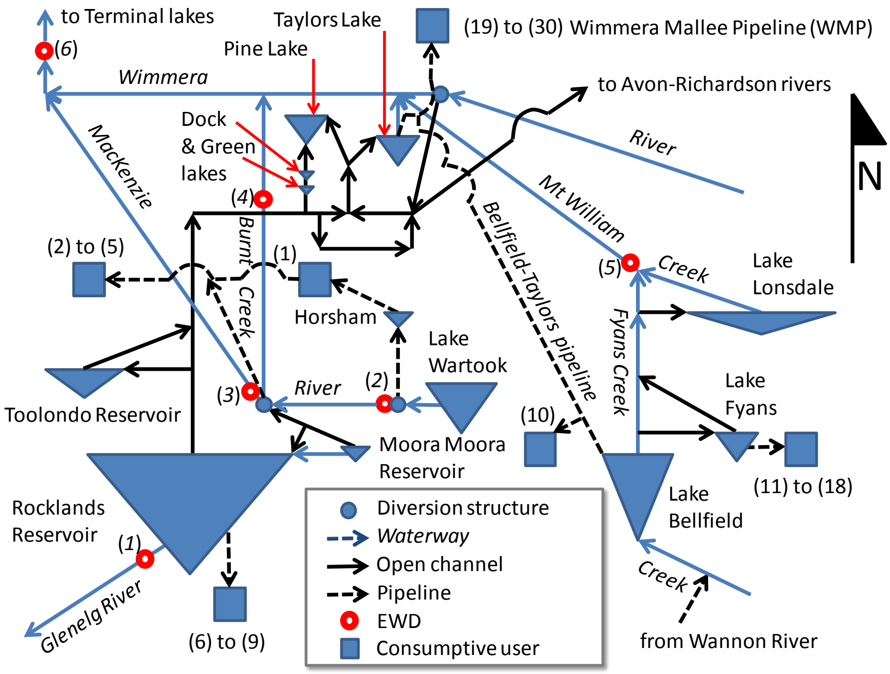
The most significant difference between the WMPP2104.sys file and the Wimmera-Glenelg REALM model was that the latter model had revised many of the carrier penalties which were interfering with the storage targets. This change resulted in a marked improvement in the stability of the Wimmera-Glenelg REALM model in terms of a reduced number of convergence failures. A brief summary was provided in terms of the methodology for the derivation of the hydro-climatic and water demand inputs for the three hydro-climatic conditions viz. historic, low to medium level, and medium to high level GHG emissions. It was explained that there were 9 rainfall inputs, 18 evaporation inputs, and 21 streamflow inputs which represented one of the three hydro-climatic conditions; 30 consumptive water demands which were static and the same for all three hydro-climatic conditions; and 6 environment water demands (EWDs) which had a static and a variable component. The setup of the optimisation engine was described in terms of the detailed workings of the NSGA-II. The sorting procedure of the NSGA-II was presented in the first instance together with the niching strategy (which uses the crowding distance (d)). It was explained that the niching strategy provided a means for ensuring a diverse set of operating plans with the continued convergence of the NSGA-II towards the Pareto front. The genetic operators (i.e. selection, crossover, and mutation) were described in terms of a sample higher order MOOP starting from the parent population through to the offspring population of candidate optimal operating plans. The adoption of the optimisation parameters largely relied on the outcomes of separate studies together with six O-S model runs which were used to show the sensitivity of different optimisation parameter settings in terms of the diversity of optimal operating plans along the Pareto front. The adopted optimisation parameters were $\mathrm{p_s} = 1,\ \mathrm{p_c} = 0.8,\ \mathrm{p_m} = 0.2, \mathrm{N} = 100$.

Section 3.5 presented sustainability indices for the WGWSS which were developed for the purposes of analysing and ranking optimal operating plans from the Pareto front. The Sustainability Index (SI) for the WGWSS was developed from the hierarchical structure of the higher order MOOP described in Section 3.3. The highest level represented the SI which was used to evaluate optimal operating plans with respect to all the major interests for water in the WGWSS. The second level of the SI was expressed in terms of a Component-level Index for the i^{th} interest for water (CI_i) viz. (CI_{env}) for the environmental interests, (CI_{socio}) for the social interests, (CI_{cons}) for the consumptive interests and (CI_{sys}) for the system-wide interests for water. The lowest level of the SI featured the 18 performance metrics which were used to provide the important link between the interests for water in the WGWSS and the search for candidate optimal operating plans. As such, it was shown that the SI provided the basis for the development of optimal operating plans for the WGWSS which have sustainability as an overall goal. The reasons for using a multiplicative aggregation scheme for the SI were explained. The main benefits of this geometric average aggregation were that the SI would have increased flexibility to include a wide range of interests for water and to express these in terms of any number of performance metrics; and that it would have better scaling characteristics so that the SI would not obscure poor performance as compared to the arithmethic average. It was considered that such scaling characteristics would assist the DM to reach consensus amongst competing interests for water by favouring optimal operating plans that had *good* values for all metrics (of all interests for water). It was explained that the process of ranking optimal operating plans from the Pareto front brought together two aspects of multi-objective optimisation, namely; (i) the quantitative information regarding the characteristics of the optimal operating plans along the Pareto front; and (ii) the higher level qualitative information in the form of stakeholders' preferences. The quantitative information was provided by the SI and its ability to evaluate and compare optimal operating plans in both the objective space and the decision space. With respect to the qualitative information, the use of the SI was extended to incorporate (i) the j^{th} stakeholder's weight for the m^{th} performance metric (w_m^j); and (ii) a weighted (geometric average) multiplicative aggregation scheme. The resulting weighted sustainability index was referred to as the "Weighted Sustainability Index" (SI^j) for the j^{th} stakeholder. It was explained that the SI^j had all the benefits of the SI in terms of flexibility and scalability as described earlier and that it also provided continuity in the multi-criterial decision-making process i.e. from evaluation of optimal operating plans through to the selection of a preferred optimal operating plan.

Chapter 4. Analysis of optimal operating plans using the Sustainability Index (SI)

4.1 Introduction

This chapter describes the effectiveness of the Sustainability Index (SI) in terms of analysing optimal operating plans along the Pareto front obtained using multi-objective optimisation under historical hydro-climatic conditions. Specifically, it presents an analytical approach that deals with (i) ranking alternatives; (ii) assessing the level of influence that a set of operating rules has on a system's sustainability; and (iii) showing the effect of alternative operating plans on various interests for water. For this purpose, various multi-objective optimisation problems (MOOPs) are formulated for the Wimmera-Glenelg Water Supply System (refer Figure 4.1) and solved using the optimisation-simulation (O-S) modelling approach described in Chapter 3. Note that Figure 4.1 is the same schematic previously used in Figure 3.2.



Note: Numbers in brackets refer to environmental water demands or EWDs (italic font) and consumptive water demands (regular font) configured in the Wimmera-Glenelg REALM model (refer to Section 3.2.2).

Figure 4.1 Schematic of the Wimmera-Glenelg Water Supply System (not to scale)

Chapter 3 described important factors related to solving higher order MOOPs which influenced the research methodology, viz; the slow convergence of solutions to the Pareto front; and the high computational costs required to progress this search. An increase in objectives has the effect of slowing the progression (i.e. *convergence*) of the population of solutions to the Pareto front. This slow convergence is largely attributed to the dominance test which is applied to the solutions of the population; resulting in a greater number of O-S modelling generations to progress the solutions towards the Pareto front. The term *generation* refers to a (single) iteration of the O-S model. An increase in the number of generations requires greater computational processing effort, which may be addressed through parallel computing processes. However, such parallel computing capabilities were not available for this thesis, which meant that simulation runs for all solutions of the population had to be completed in series (i.e. one run at a time) before the optimisation search could be executed. For these reasons (of slow convergence and high computational costs), the number of generations performed by the O-S model was limited to five in number (throughout this thesis). Importantly, this is not to be mistaken as a research limitation given that the novelty of this study is that of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*.

Chapter 3 also described an approach for the formulation of MOOPs and applied it to a higher order MOOP which was used to support the development of optimal operating plans for the Wimmera-Glenelg Water Supply System (WGWSS). A higher order MOOP is defined in this thesis as a problem that is formulated with more than three objective functions. All the major interests for water were explicitly taken into account and were used as the basis for 18 objective functions which directed the search towards the set of optimal operating plans which were collectively referred to as the *Pareto front*. The decision variables were expressed in terms of 24 water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. For the reader's convenience and for completeness of Chapter 4, these planning decisions are provided again in Table 4.1. There are six categories of decision variables representing *priorities of supply* between different sources of supply and between different user groups; *storage flood reserve volumes* to provide flood attenuation; *environmental allocation shares* for apportioning environmental water allocations between river basins; the preference of alternative *flow paths* for the harvesting and/or transfer of water; *storage maximum operating volumes* for the key water harvesting storages; and *storage draw down priorities and storage targets.*

Table 4.1 Water management planning decisions for the WGWSS

Category	dv_x	Decisions	Value range
Priority of supply	dv_1	Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?	Either Lake Wartook or Moora Moora Reservoir is first priority and the other is a supplementary source of supply
	dv_2	Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?	Either Horsham (1) or EWD (2) is satisfied first
	dv_3	Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?	Either harvest flows into Taylors Lake or EWD (3) is satisfied first
	dv_4	Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?	Either harvest flows into Taylors Lake or EWD (4) is satisfied first
	dv_5	Should consumptive demands (6) to (9) be satisfied before the EWDs in Glenelg River (1) or vice versa?	Either consumptive demands (6) to (9) or EWD (1) is satisfied first
	dv_6	Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir or vice versa?	Either harvest flows into WIC or provide passing flow (6) first
	dv_7	Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?	Either hold water in Lake Lonsdale for consumptive demands (19) to (30) or supply EWD (5) first
Flood reserve volume	dv_8	How much flood reserve should be provided at Lake Wartook in June?	Either hold no reserve or hold a maximum of up to the full storage capacity in June
Share of environ-mental allocation	dv_9	How much of the environmental water allocation should be released in the Glenelg River basin?	Either no share or up to 100% of the environmental water allocation
	dv_{10}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Wartook?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin
	dv_{11}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Lonsdale?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin and that at Lake Wartook
Flow path	dv_{12}	Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?	Either harvest flows into Wimmera Inlet Channel or pass all flows to Wimmera River
	dv_{13}	Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?	Supply from Lake Bellfield may result in one of three outcomes; nil, a proportion based on the volume in storage, or 100%
Storage maximum operating volume	dv_{14}	Toolondo Reservoir	0 to 92,430 ML
	dv_{15}	Lake Lonsdale	Inlet is either open or closed
	dv_{16}	Lake Bellfield	0 to 76,000 ML
	dv_{17}	Taylors Lake	0 to 33,700 ML
	dv_{18}	Rocklands Reservoir	0 to 348,000 ML
	dv_{19}	Lake Lonsdale	0 to 65,000 ML
	dv_{20}	Moora Moora Reservoir	0 to 6,300 ML
Storage draw down priority and storage target	dv_{21}	What should be the drawdown priority of the headworks storages?	Each storage is assigned a unique draw down priority from 1 to 8
	dv_{22}	What should be the second point on the target curve for the headworks storages?	Any volume between dead storage and FSL
	dv_{23}	What should be the third point on the target curve for the headworks storages?	Any volume between the second target point and FSL
	dv_{24}	What should be the fourth point on the target curve for the headworks storages?	Any volume between the third target point and FSL

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
'EWDs' refers to environmental water demands.
Number in brackets refers to consumptive user demand centres and environmental flow sites shown in Figure 4.1.

Chapter 3 presented the SI as a means to evaluate and compare alternative operating plans and highlighted the following key benefits to the use of the SI in higher order MOOPs:

a) The SI provides a link between the interests for water and the objective functions as part of the formulation of the MOOP and so allows for the search of optimal operating plans that are relevant to the DM. This potentially increases the efficiency of the search process and reduces computational effort. The search process here refers to the progression of the O-S modelling procedure towards the Pareto front.

b) By virtue of the SI being applied after the optimal operating plans are found by the O-S modelling approach -

- The SI is consistent with the ideal multi-objective optimisation approach. Deb (2001) described the ideal multi-objective optimisation approach in two steps where the first step involves finding a diverse set of optimal solutions and the second step involves choosing one of the solutions using higher-level qualitative information. It was shown that the SI could be used as part of the second step given its mathematical structure was able to be adapted for the inclusion of the DMs' relative weights.
- The SI does not introduce bias in the search process. As the O-S modelling procedure is performed before the SI, all objectives are considered to be equally important.
- The SI avoids the need to repeat the search process in situations where the DM's preferences change over time. DMs' preferences may change over time due to the social learning process that occurs as part of the selection of a preferred optimal solution.

One of the main constituents of the SI were described in terms of four component-level indices that are used for the evaluation and comparison of optimal operating plans within Chapter 4. For the reader's convenience and for completeness of Chapter 4 these component-level indices are provided again in Equations 4.1 to 4.4. The Component-level Index (CI_i) assumes that the sustainability for the i^{th} interest for water is measured in terms of reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i).

These interests for water identified in Chapter 3 are broadly classified into environmental (env); social interests such as for recreation at Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR); consumptive interests ($cons$); and all these interests collectively in terms of system water allocations ($alloc$). Equation 4.5 is the mathematical expression for the SI. The reader is referred to Section 3.5.1 for further details regarding the basis of these equations.

$$CI_{env} = [Rel_{env} \times Res_{env} \times (1 - Vul_{env})]^{1/3} \tag{4.1}$$

$$CI_{socio} = [Rel_{LL} \times Res_{LL} \times (1 - Vul_{LL}) \times Rel_{LF} \times Res_{LF} \times (1 - Vul_{LF}) \times Rel_{RR} \times Res_{RR} \times (1 - Vul_{RR})]^{1/9} \tag{4.2}$$

$$CI_{cons} = [Rel_{cons} \times Res_{cons} \times (1 - Vul_{cons})]^{1/3} \tag{4.3}$$

$$CI_{sys} = [Rel_{alloc} \times Res_{alloc} \times (1 - Vul_{alloc})]^{1/3} \tag{4.4}$$

$$SI = \left[(CI_{env})^3 \times (CI_{socio})^9 \times (CI_{cons})^3 \times (CI_{sys})^3\right]^{1/18} \tag{4.5}$$

For the purposes of assessing the effectiveness of the SI in terms of ranking optimal operating plans, a *lower order* MOOP concerning environmental flows is presented. A lower order MOOP is a problem that is formulated with two or three objective functions. The three environmental objectives are expressed in terms of environmental flow deficits and are defined in Section 4.2.1. This MOOP is solved for seven decision variables that represent the storage maximum operating volumes of six headworks storages within the WGWSS (refer to Table 4.1 - dv_{14} to dv_{20}). As explained in Section 3.3.1.5, maximum operating volumes are used to provide environmental (unregulated) flows in the form of storage spills and also to reduce storage evaporative losses. In general, a system which has very high maximum operating volumes runs the risk of not delivering the required frequency and volume of large environmental flows (or "high fresh flows"). Conversely, a system which has very low maximum operating volumes runs the risk of not being able to reserve sufficient resources for essential services during periods of low inflow. The O-S modelling results for the optimal operating plans are analysed in terms of the objective space and the decision space. In the objective space, the results are presented as a three dimensional Pareto front using a Cartesian coordinate system. This visualisation approach is compared to an equivalent representation using the SI in terms of its normalised rank (referred to as "SI curve"). Similarly, the decision variables for each of the optimal operating plans found are also presented and analysed with respect to the SI curve. Refer to Section 4.2 for details of this part of the study.

The level of influence that a set of operating rules has on the sustainability of the WGWSS is assessed using a series of *higher order* MOOPs. A higher order MOOP is a problem that is formulated with more than three objective functions. The higher order MOOP described in Chapter 3 (referred to as "Run (A1)") is also included as a point of reference. For each O-S modelling run, an 18-objective problem is used to search for optimal operating plans assuming all but one of the planning decision categories are fixed, at any one time, to the decision variable values as per the simulation-only base case scenario (BC01). The base case scenario represents the operating plan that is in place for the WGWSS at the time of writing of this thesis – refer to Section 3.2.2 for further details. Solving for one planning decision category in this way focuses the search on a certain section of the Pareto front and allows the exploration of optimal plans with respect to one category of operating rules. This approach produces six O-S modelling runs in total. Building on the outcomes of the lower order MOOP, the optimal operating plans found under the six runs are presented in terms of SI curves and compared to Run (A1) in order to assess the level of influence each category of operating rules has on the sustainability of the WGWSS. Refer to Section 4.3 for details of this part of the study.

Having applied the SI to a lower order MOOP (Section 4.2) and a series of higher order MOOPs (Section 4.3), this understanding of the SI can be used to show the effect of alternative operating plans on various interests for water in terms of their corresponding CI (i.e. CI_{env}, CI_{socio}, CI_{cons}, and CI_{sys}). This part of the study does not introduce any additional O-S model runs; instead it investigates two optimal operating plans under the aforementioned Run (A1) in terms of the objective space and decision space. In order to appreciate the full range of optimal operating plans that have been found, the two plans selected for analysis correspond to those that achieve the highest and lowest SI. As for the SI, the operating plans are also compared using the CI in terms of its normalised rank (referred to as "CI curve"). These operating plans are compared to the base case operating plan (BC01) in order to highlight the differences in system behaviour over the planning period. Refer to Section 4.4 for details of this part of the study.

4.2 A lower order MOOP - one user group

The purpose of the lower order MOOP presented in this section is to assess the effectiveness of the SI curve in the visualisation of the optimal operating plans that lie on the Pareto front. A lower order MOOP is used for this investigation as the modelling results can be presented on a two dimensional plane whereby each orthogonal axis represents an objective function. Such a visual representation allows for the exploration of a three dimensional Pareto front using a Cartesian coordinate system. This visualisation approach is compared to the corresponding SI curve.

4.2.1 Problem formulation and model setup

The problem is to optimise the system operating rules with regards to three environmental objectives expressed in terms of *nil environmental flow deficits* which seek to maximise the reliability, maximise the resiliency, and minimise the vulnerability of such deficits (refer to Section 3.2.4 for further details regarding these performance metrics). In simple terms, nil environmental flow deficits may be thought of as environmental flow demands that do not experience any shortfall in supply volume. The three objectives are given below in Equations 4.6 to 4.8 and are based on performance metrics as described in Sandoval-Solis et al. (2011). These objectives are in direct conflict with each other as increasing the reliability of nil environmental flow deficits does not necessarily equate to an increase in resiliency; nor does the increase in any or both of these two objectives (i.e. reliability and resiliency) result in reduced vulnerability of such deficits, and vice versa. For each time period $(t = \text{July to June})$, the annual environmental flow deficits $(\sum_{t=1}^{12} Def_{env,t})$ are positive when the annual environmental water demand $(\sum_{t=1}^{12} D_{env,t})$ is more than the annual water supplied $(\sum_{t=1}^{12} Q_{env,t})$, and when the water supplied is equal to the water demand $(\sum_{t=1}^{12} Q_{env,t} = \sum_{t=1}^{12} D_{env,t})$ the annual environmental flow deficits are zero $(\sum_{t=1}^{12} Def_{env,t} = 0)$. For this problem, $\sum_{t=1}^{12} Def_{env,t}$ represents the annual sum of six separate environmental flow deficits in the Glenelg River at Rocklands Reservoir, Wimmera River at Huddlestons Weir, Mt William Creek at Lake Lonsdale, MacKenzie River at Dad and Dave Weir, MacKenzie River at Distribution Heads, and Burnt Creek at Burnt Creek Channel (refer Figure 4.1). The number of time intervals $(n = 118 \text{ years})$ corresponds to the 118-year simulation period from 1891 to 2009.

$$\text{Maximise}, f_1 = Rel_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0}{n}, \text{ where } n = 118 \text{ years} \quad (4.6)$$

$$\text{Maximise}, f_2 = Res_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{env,t}) > 0}{\text{No. of times } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occured}} \quad (4.7)$$

$$\text{Minimise}, f_3 = Vul_{env} = \frac{(\sum_{t=1}^{12} Def_{env,t}) / \text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occurred}}{Average\ of\ (\sum_{t=1}^{12} D_{env,t})} \quad (4.8)$$

Subject to the constraints as configured in the revised Wimmera-Glenelg REALM model (refer Section 3.3.2).

The decision variables to solve for are dv_{14} to dv_{20} corresponding to those that define the maximum operating volumes for the storages specified in Table 4.1.

The lower order MOOP is solved for five generations using the O-S modelling approach with the following optimisation parameters: population size $(\mathrm{N}) = 100$, probability of crossover $(\mathrm{p_c}) = 0.8$, and probability of mutation $(\mathrm{p_m}) = 0.2$ (refer to Section 3.4.2.2 for further details regarding the optimisation parameters adopted).

It is important to highlight that as this lower order MOOP considers environmental objectives only, the O-S model may well find optimal operating plans that are not practical in a real world sense. For example, the O-S model may find an optimal operating plan that specifies a very low maximum operating volume for a storage that is the sole source of supply to consumptive users. Whilst the low maximum operating volume would provide high fresh flows to the waterway downstream of the storage, it could possibly cause a poor result in terms of consumptive user supply deficits in an otherwise different MOOP which includes consumptive use objectives.

4.2.2 Modelling results and discussion

4.2.2.1 Objective space

The O-S model found a total of six optimal operating plans after 1,500 simulations and 4,500 objective function evaluations i.e. a population of 100 operating plans over a period of 5 generations assuming a 3-stage evolutionary process (or 100 x 5 x 3 = 1,500 simulations), each simulation requiring evaluations with respect to 3-objective functions (or 1,500 x 3 = 4,500 evaluations). The 3-stage evolutionary process used in the Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) is explained in Section

2.3.1.2(a). The remaining 94 operating plans were either duplicates of the six optimal plans or inferior with respect to these six plans (refer Equation 2.2 for further details regarding the possible outcomes from the dominance test). Figure 4.2 shows the six optimal operating plans and also the base case operating plan (BC01) which is included as a point of reference.

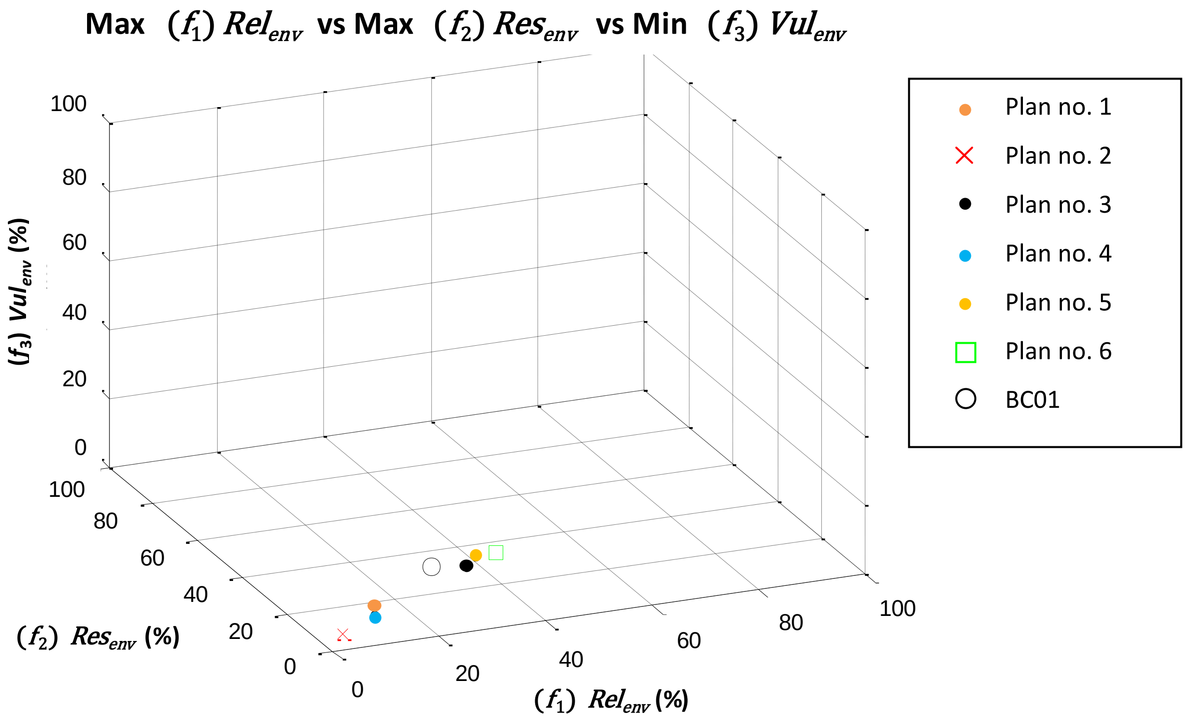


Figure 4.2 3-D (x-y-z) plot of six optimal operating plans for the lower order MOOP and the base case operating plan (BC01)

The visualisation of the Pareto front for this lower order MOOP is straightforward using a three-dimensional Cartesian coordinate plane. For ease of analysis of the Pareto front, the corresponding two-dimensional plots for (f_1) Rel_{env} and (f_2) Res_{env} , (f_1) Rel_{env} and (f_3) Vul_{env} , and (f_2) Res_{env} and (f_3) Vul_{env} are also provided in Figure 4.3, Figure 4.4, and Figure 4.5 respectively.

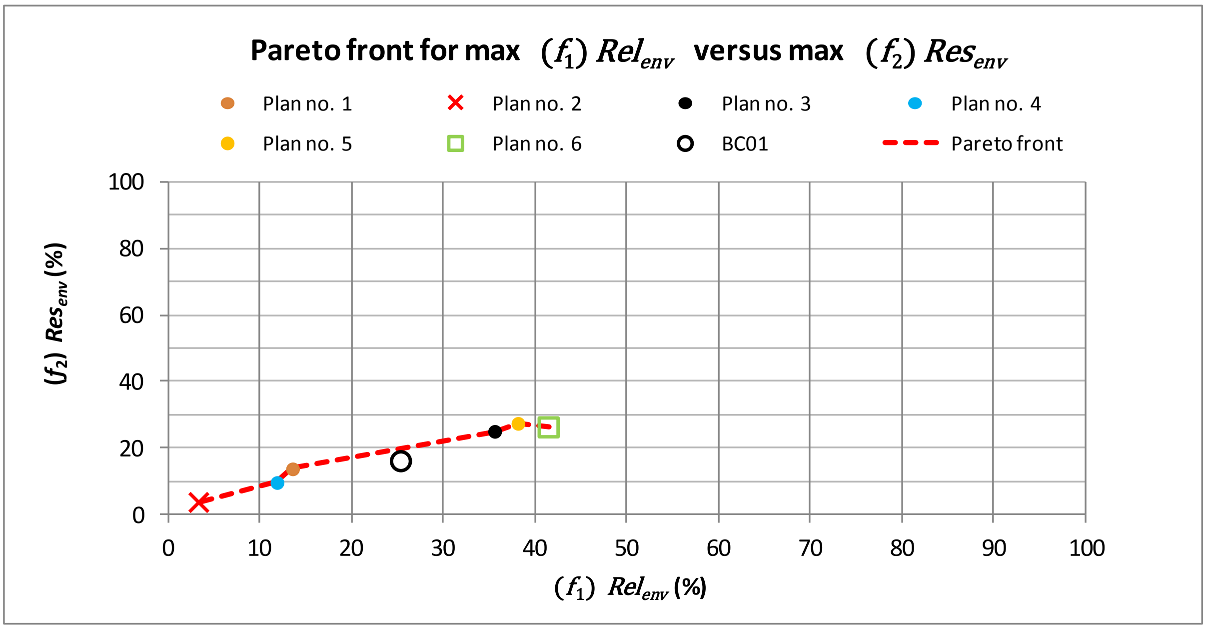


Figure 4.3 2-D (x-y) plot of Pareto front for the lower order MOOP

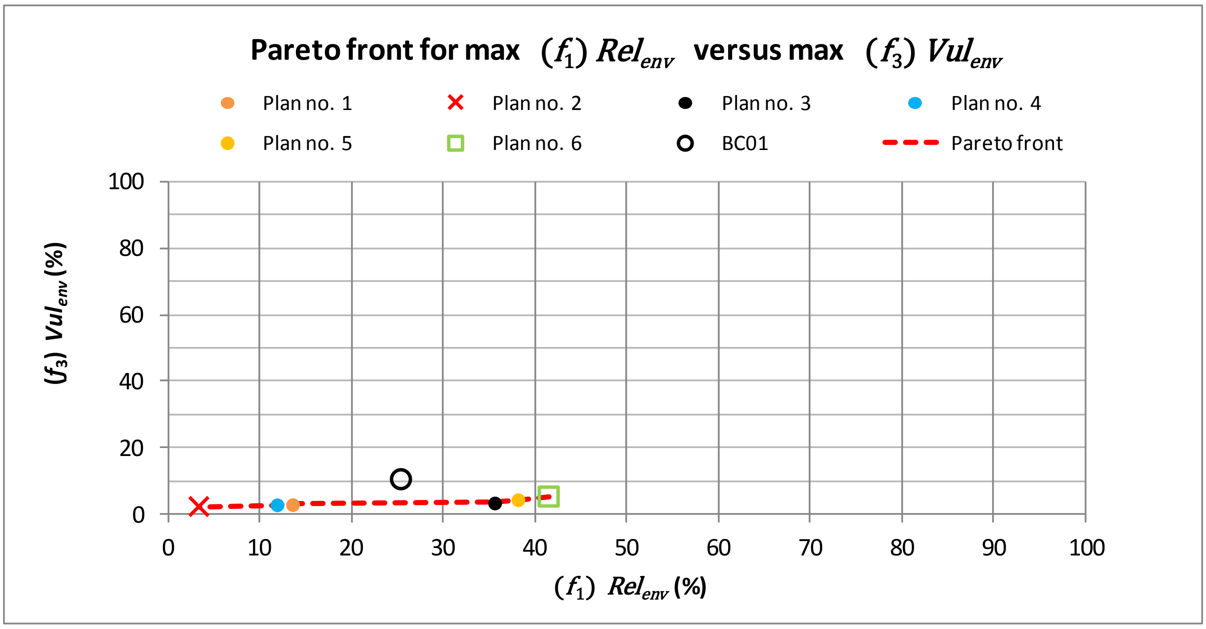


Figure 4.4 2-D (x-z) plot of Pareto front for the lower order MOOP

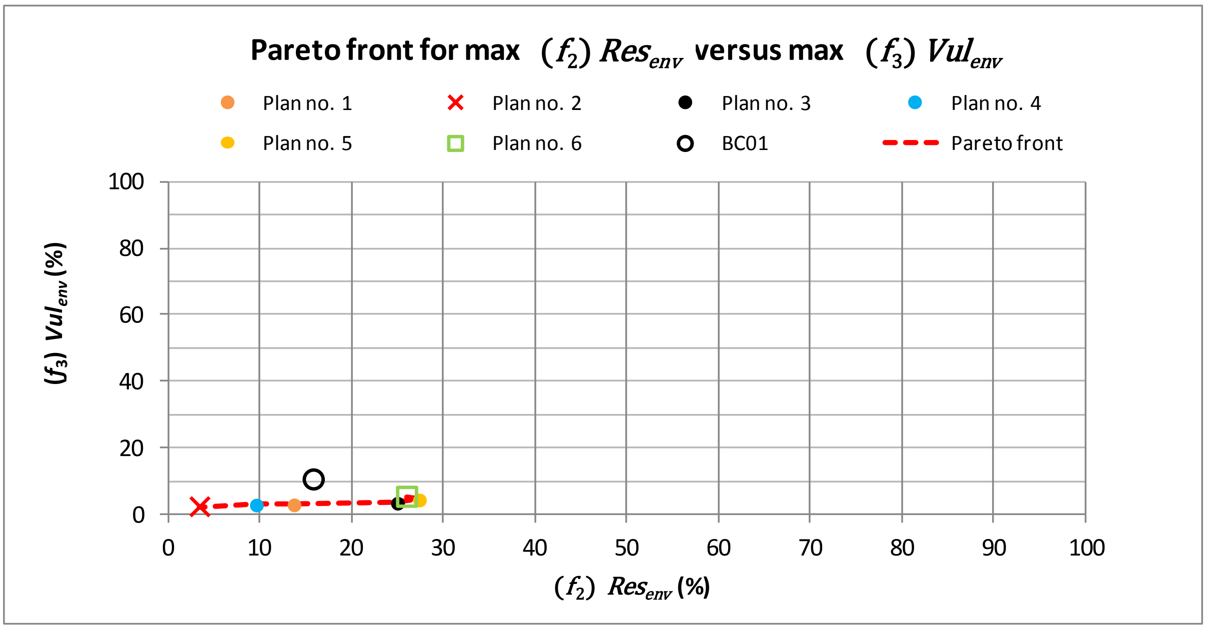


Figure 4.5 2-D (y-z) plot of Pareto front for the lower order MOOP

Table 4.2 summarises the change in reliability, resiliency, and vulnerability of operating Plan no. 1 to Plan no. 6 relative to BC01 based on the results shown in Figure 4.3, Figure 4.4, and Figure 4.5 respectively. The tabular results below confirm that the reason that BC01 does not lie on the Pareto front (as shown in Figure 4.3 to Figure 4.5) is because it is worse than Plan no. 6, Plan no. 5, and Plan no. 3 in all objectives.

Table 4.2 Change in reliability, resiliency, and vulnerability of Plan no. 1 to Plan no. 6 relative to the base case operating plan (BC01)

	Change in reliability (Rel), resiliency (Res), and vulnerability (Vul) of Plan no. 1 to Plan no. 6 relative to base case operating plan (BC01)		
	(f_1) Rel_{env}	(f_2) Res_{env}	(f_3) Vul_{env}
Plan no. 1	-11.9% (13.6% - 25.4%)	-2.2% (13.7% - 15.9%)	-7.5% (2.9% - 10.4%)
Plan no. 2	-22.0% (3.4% - 25.4%)	-12.4% (3.5% - 15.9%)	-8.2% (2.2% - 10.4%)
Plan no. 3	10.2% (35.6% - 25.4%)	9.1% (25.0% - 15.9%)	-7.0% (3.4% - 10.4%)
Plan no. 4	-13.6% (11.9% - 25.4%)	-6.3% (9.6% - 15.9%)	-7.6% (2.8% - 10.4%)
Plan no. 5	12.7% (38.1% - 25.4%)	11.5% (27.4% - 15.9%)	-6.1% (4.4% - 10.4%)
Plan no. 6	16.1% (41.5% - 25.4%)	10.2% (26.1% - 15.9%)	-5.2% (5.2% - 10.4%)
BC01	na	na	na

'na' means not applicable

The differences shown in Table 4.2 are used as a means to trade-off each of the six optimal operating plans against BC01. For example, selecting Plan no. 6 in preference to BC01 means that the operating rules would achieve nil environmental flow deficits that are 16.1% more reliable, 10.2% more resilient and 5.2% less vulnerable than the deficits under BC01. In this instance, Plan no. 6 is clearly the better solution with respect to all objectives. Comparing the results for Plan no. 2 with BC01, shows that the operating rules under Plan no. 2 would achieve nil environmental flow deficits that are 22% less reliable, 12.4% less resilient, and 8.2% less vulnerable than the deficits under BC01. Despite BC01 achieving a better result than Plan no. 2 in terms of two objectives (i.e. reliability and resiliency), Plan no. 2 is not inferior to BC01 as Plan no. 2 is better than BC01 in at least one objective (i.e. vulnerability).

From Equation 4.1, the Component-level Index (CI_{env}) values for each of the six optimal operating plans found and BC01 are calculated and ranked from highest to lowest SI in Table 4.3 and plotted against its normalised rank in Figure 4.6. Note that as this MOOP concerns environmental interests for water only, $SI = CI_{env}$ in the absence of any other component-level index. Both Table 4.3 and Figure 4.6 show that the SI of Plan no. 6 is the highest (0.47) and Plan no. 2 is the lowest (0.11). Note that the SI of BC01 (i.e. 0.33) is not included in Table 4.3 and Figure 4.6 as BC01 does not lie on the Pareto front.

Table 4.3 Objective function value, Sustainability Index, and crowding distance for optimal operating plans

	Objective function value			Sustainability Index (SI)	Crowding distance (d)	Average crowding distance (d_{av})
	(f_1) Rel_{env}	(f_2) Res_{env}	(f_3) Vul_{env}			
Plan no. 6	41.5%	26.1%	5.2%	0.47	∞	na
Plan no. 5	38.1%	27.4%	4.4%	0.46	∞	na
Plan no. 3	35.6%	25.0%	3.4%	0.44	1.65	1.55
Plan no. 1	13.6%	13.7%	2.9%	0.26	1.45	
Plan no. 4	11.9%	9.6%	2.8%	0.22	0.92	1.18
Plan no. 2	3.4%	3.5%	2.2%	0.11	∞	na
BC01	*25.4%*	*15.9%*	*10.4%*	*na*	*na*	*na*

'na' means not applicable

Table 4.3 also shows the crowding distance (d) for all six optimal operating plans. As explained in Section 2.3.1.2(a), the crowding distance is a measure of the density of solutions surrounding a particular solution in the population with respect to all objectives. It represents the diversity amongst optimal operating plans along the Pareto front. Note that the crowding distances for Plan no. 6, Plan no. 5, and Plan no. 2 are equal to ∞ as these are considered to be boundary solutions in the crowding distance calculation. The average of the crowding distances (d_{av}) for Plan no. 3 and Plan no. 1 is greater than that for Plan no. 1 and Plan no. 4 i.e. $1.55 > 1.18$. Note that the crowding distances for Plan no. 6, Plan no. 5, and Plan no. 2 are not included in the average crowding distance as these are considered to be boundary solutions as mentioned earlier. This means that Plan no. 1 and Plan no. 4 are more tightly clumped together than Plan no. 3 and Plan no. 1. This effect is shown graphically in Figure 4.6 whereby the gradient in the curve between Plan no. 3 and Plan no. 1 is greater than that for the section of curve between Plan no. 1 and Plan no. 4. Therefore, in addition to the SI curve informing the DM of the sustainability of an optimal operating plan, the gradient of the SI curve also provides the DM with a sense of the diversity of plans in a particular section of the curve. This important outcome highlights one of the major benefits of using the SI curve for ranking optimal operating plans with respect to many objectives and many alternative operating plans as generally occurs in higher order MOOPs.

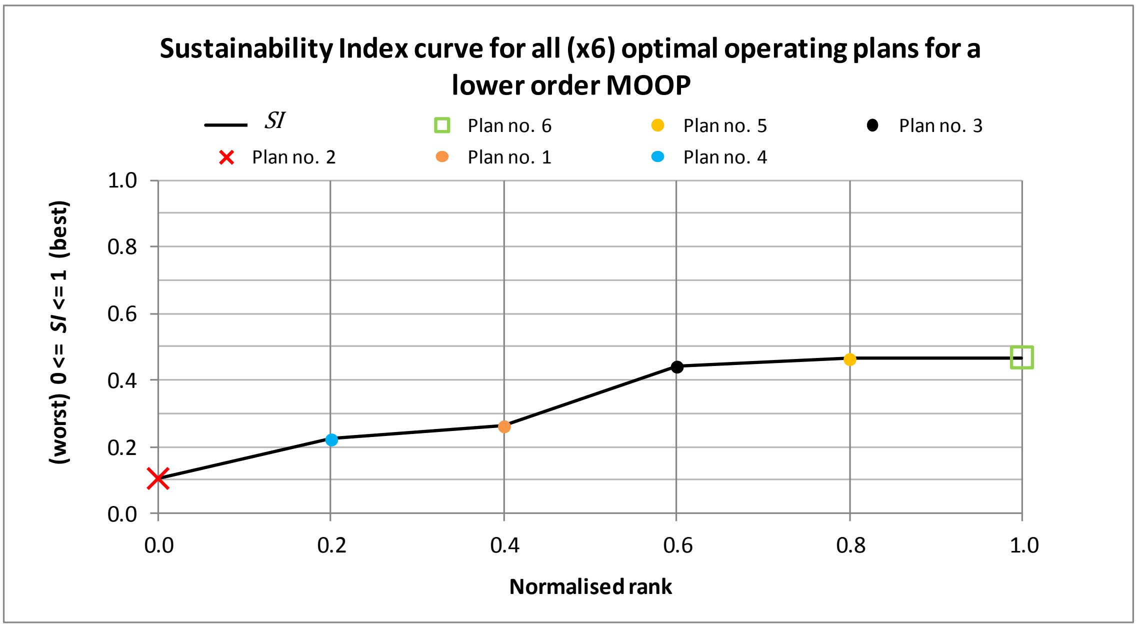


Figure 4.6 Sustainability Index curve for a lower order MOOP

4.2.2.2 Decision space

In addition to analysing the objective space, the SI curve may be used to provide a meaningful basis from which to compare various alternatives in the decision space. Figure 4.7 to Figure 4.13 show the storage maximum operating volumes for each of the six optimal plans found by the O-S model together with the SI curve (shown in Figure 4.6). In each case, the decision variable values for the highest ranked SI operating plan (Plan no. 6) and the lowest ranked SI operating plan (Plan no. 2) are highlighted in order to provide a point of reference with regards to the level of sustainability that would be achieved for the WGWSS. According to GWMWater (2011), Toolondo Reservoir is primarily used as a balancing storage in conjunction with Rocklands Reservoir in order to maximise the efficiency of harvesting from the upper Glenelg River with transfers to Taylors Lake downstream of Toolondo Reservoir (refer Figure 4.1). For this reason it is helpful to analyse the modelling results for these storages with respect to all three decision variables together i.e. dv_{18} (Rocklands Reservoir - Figure 4.7), dv_{14} (Toolondo Reservoir - Figure 4.8), and dv_{17} (Taylors Lake – Figure 4.9).

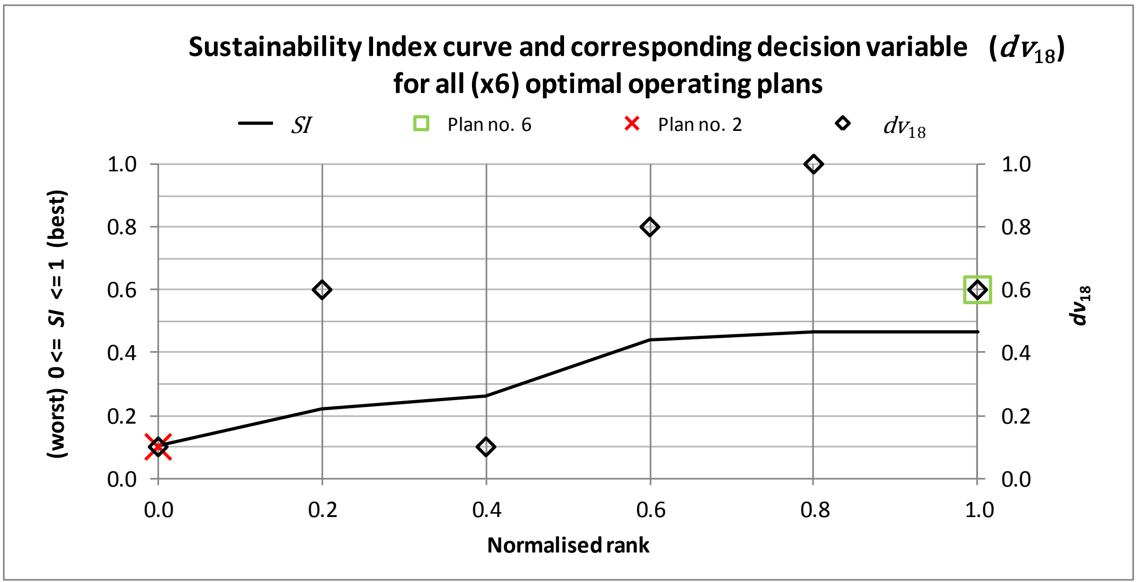


Figure 4.7 Sustainability Index curve and corresponding decision variable (dv_{18}) for maximum operating volume at Rocklands Reservoir

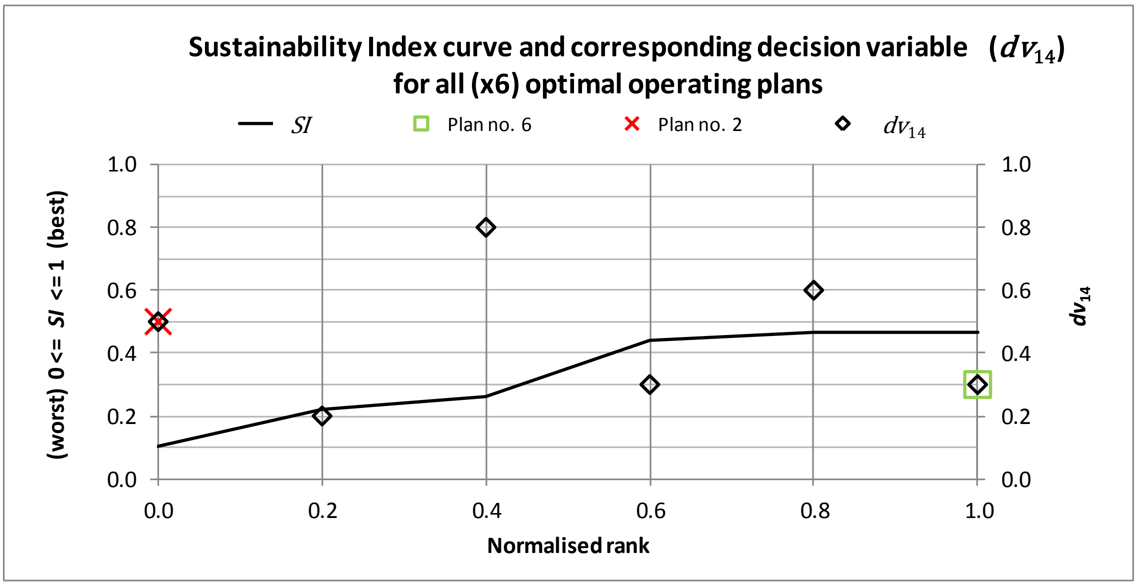


Figure 4.8 Sustainability Index curve and corresponding decision variable (dv_{14}) for maximum operating volume at Toolondo Reservoir

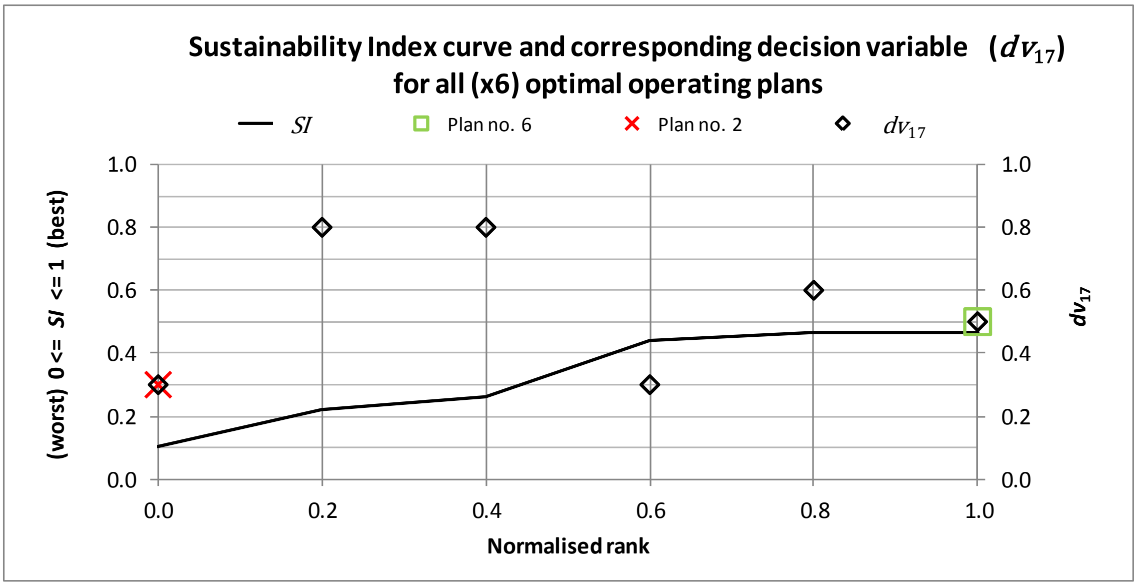


Figure 4.9 Sustainability Index curve and corresponding decision variable (dv_{17}) for maximum operating volume at Taylors Lake

This visualisation of the decision space allows the DM to investigate an optimal operating plan of interest and ascertain the value of the decision variable(s) that represents a given operating rule. For instance, the maximum operating volumes under the highest ranked *SI* operating plan (Plan no. 6) are 0.6 for Rocklands

Reservoir, 0.3 for Toolondo Reservoir, and 0.5 for Taylors Lake. These decision variable values represent a proportion of the storage's full supply volume as given in Section 3.3.1.5.

These figures also allow the DM to view the range of optimal operation for a given operating rule. For example, Rocklands Reservoir has a greater range of optimal operation in terms of maximum operating volume than does Taylors Lake ($0.1 \leq dv_{18} \leq 1.0$ cf. $0.3 \leq dv_{17} \leq 0.8$). Moreover, the DM is able to understand the implications of these planning decisions with respect to the sustainability of the system (in terms of SI). For instance, the O-S modelling results show that higher levels of sustainability are achieved for the WGWSS when Rocklands Reservoir has a maximum operating volume within its top range (i.e. $dv_{18} = 0.8$ approx.) and the other two storages within their respective lower ranges (i.e. Toolondo Reservoir: $dv_{14} = 0.4$ approx., Taylors Lake: $dv_{17} = 0.4$ approx.).

Lake Bellfield is the primary source of supply to much of the Wimmera Mallee Pipeline - see consumptive user (19) to (30) in Figure 4.1. For this reason, it is operated to full supply volume except over the April to September period when it is lowered to 76,000 ML, about 2,500 ML below FSV (GWMWater, 2011). The lowering of volume over this period is for dam safety reasons and also to absorb and manage flood flows. Figure 4.10 shows that the maximum operating volume for all but the lowest ranked SI operating plan (i.e. Plan no. 2) is within the range of 0.1 and 0.2 for Lake Bellfield. As explained earlier in Section 4.2.1, as the environmental objectives do not consider the interests of consumptive users, the lower maximum operating volumes found by the O-S model would probably have implications for consumptive users particularly those supplied via the Wimmera Mallee Pipeline.

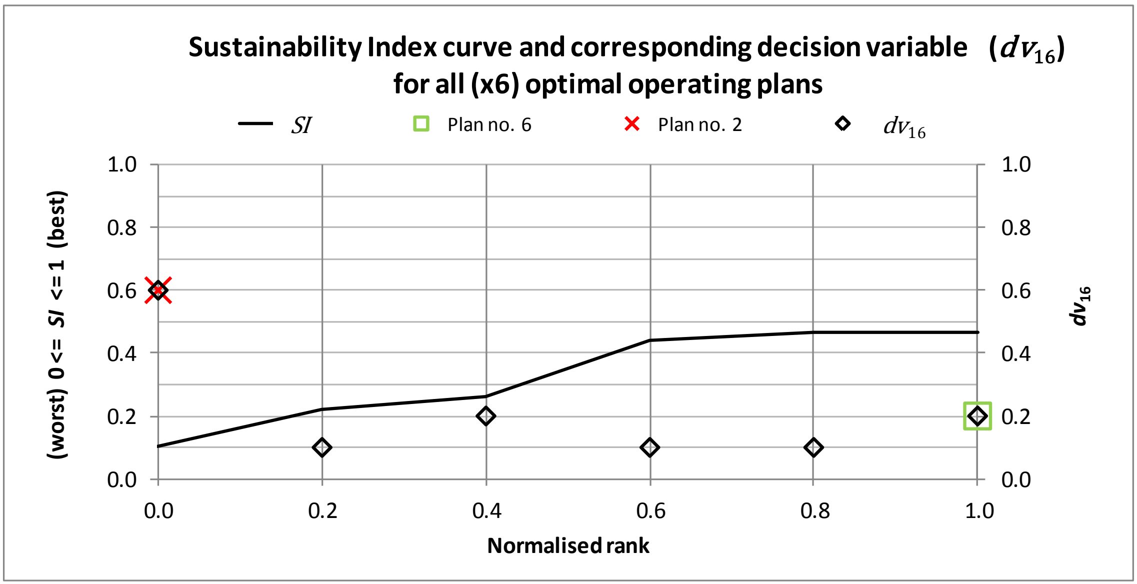


Figure 4.10 **Sustainability Index curve and corresponding decision variable (dv_{16}) for maximum operating volume at Lake Bellfield**

As explained in Section 3.3.1.5, Lake Lonsdale requires two decision variables to control the maximum operating volume due to it having its own catchment and a bypass channel. Decision variable dv_{15} controls the flow of water entering the storage and has a value of either 0 or 1, where 0 means that the inlet is completely closed and 1 represents a fully opened inlet. Decision variable dv_{19} controls the storage operating volume and has a value between 0 and 1, where 0 means that the storage is effectively not used or decommissioned and 1 represents a maximum operating volume at FSV. Figure 4.11 shows that all operating plans found by the O-S procedure have a value of 1 for dv_{15} corresponding to the inlet being open with no flow bypassing the storage. Figure 4.12 shows that the value range for dv_{19} is between 0.5 and 1 for the six plans found.

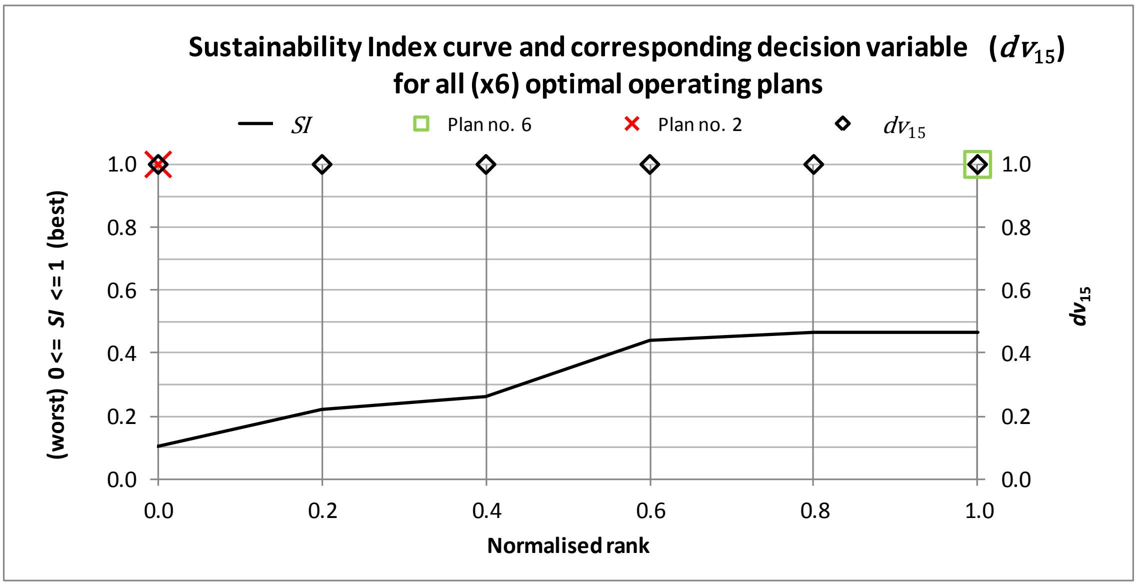


Figure 4.11 **Sustainability Index curve and corresponding decision variable (dv_{15}) for maximum operating volume at Lake Lonsdale (via inlet)**

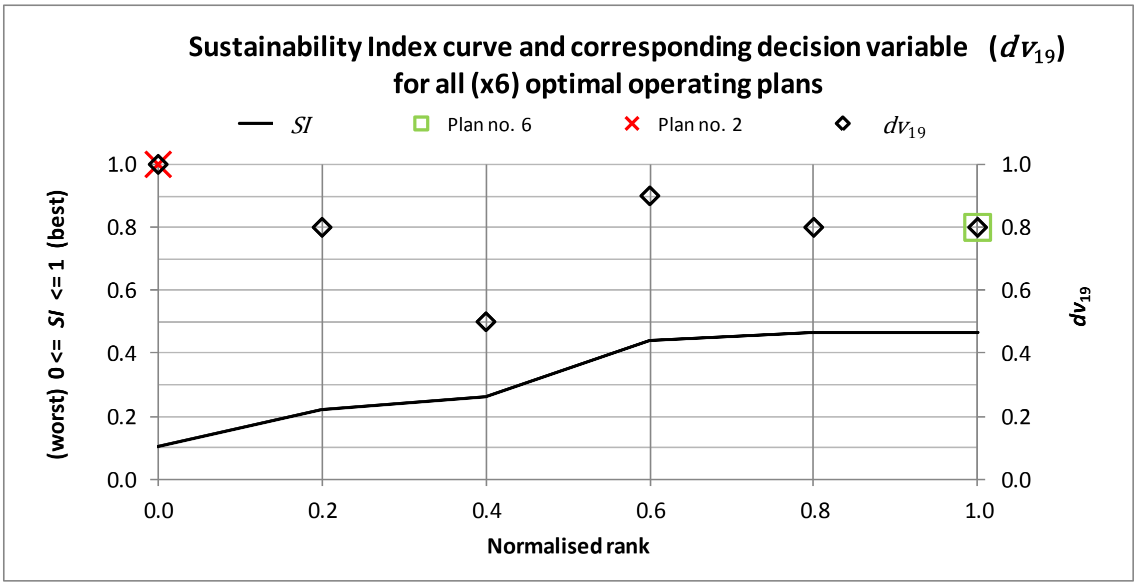


Figure 4.12 **Sustainability Index curve and corresponding decision variable (dv_{19}) for maximum operating volume at Lake Lonsdale (via outlet)**

With respect to both decision variables dv_{15} and dv_{19}, the O-S modelling results show that the highest ranked SI operating plan and the lowest ranked SI operating plan have almost identical values (i.e. Plan no. 6: $dv_{15} = 1$, $dv_{19} = 0.8$ cf. Plan no. 2: $dv_{15} = 1$, $dv_{19} = 1$). Moreover the dv_{15} and dv_{19} values for all operating plans indicates that the optimal operation of the WGWSS with respect to the three environmental objectives is largely unaffected to changes in these decision variables provided that the inlet is open and the maximum operating volume for Lake Lonsdale is greater than half its full supply volume.

Figure 4.13 shows that higher levels of sustainability for the WGWSS are achieved when Moora Moora Reservoir has a maximum operating volume within its top range (i.e. $dv_{20} = 0.7$ approx.).

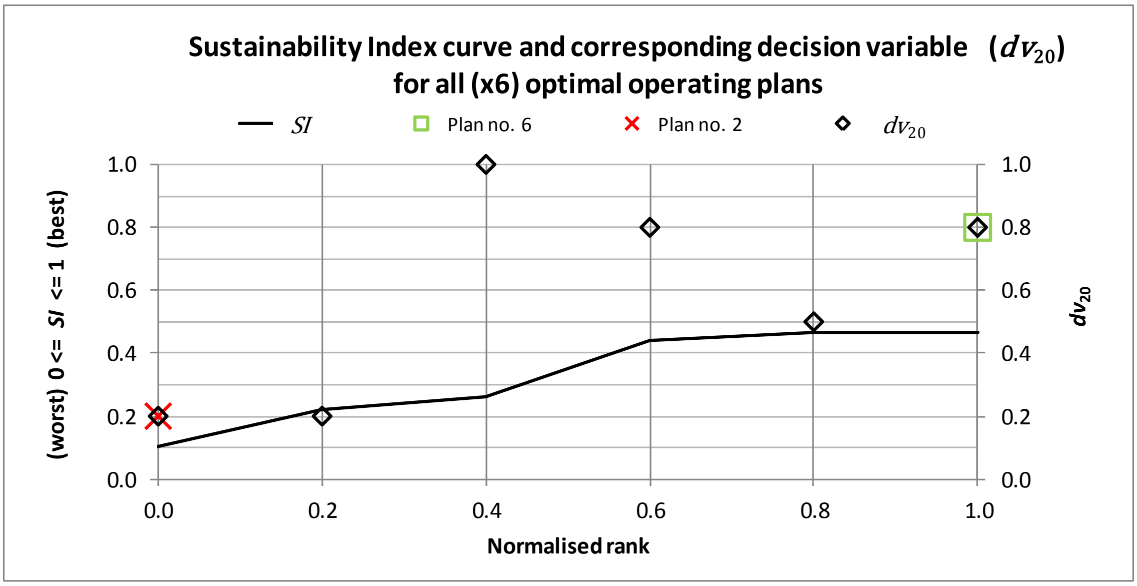


Figure 4.13 Sustainability Index curve and corresponding decision variable (dv_{20}) for maximum operating volume at Moora Moora Reservoir

4.2.2.3 <u>Discussion</u>

Table 4.4 summarises the aforementioned decision variables for each of the optimal plans analysed thus far in terms of diminishing levels of sustainability and the corresponding total maximum operating volumes. In general, the total maximum operating volumes are higher for the highest three ranked SI operating plans than the lowest three ranked SI operating plans. Interestingly, operating Plan no. 6 and Plan no. 4 show that achieving a similar total maximum operating volume alone does not necessarily result in similar levels of sustainability. This confirms that the relativity of the maximum operating volumes of reservoirs across the system also affects sustainability and that there are various optimal combinations of maximum operating volumes for the DM to consider. In this instance, the SI for operating Plan no. 4 is less than for Plan no. 6 due to the significant reductions in maximum operating volumes at Toolondo Reservoir, Lake Bellfield, and Moora Moora Reservoir which are not able to compensate for the increase in maximum operating volume at Taylors Lake. This reduced performance of the WGWSS under Plan no. 4 is reflected in the lower levels of reliability, resiliency, and vulnerability as depicted in Table 4.3 (i.e. Plan no. 6: $Rel_{env} = 41.5\%, Res_{env} = 26.1\%, Vul_{env} = 5.2\%$ cf. Plan no. 4: Rel_{env} = 11.9%, Res_{env} = 9.6%, Vul_{env} = 2.8%).

Table 4.4 Storage maximum operating volumes (in ML) and Sustainability Index (italics) for the six optimal operating plans for the lower order MOOP

Decision variable	Storage maximum operating volumes (ML)					
	Plan no. 6	Plan no. 5	Plan no. 3	Plan no. 1	Plan no. 4	Plan no. 2
dv_{14} (Toolondo Reservoir)	27,729	55,458	27729	73944	18,486	46,215
dv_{16} (Lake Bellfield)	15,200	7,600	7600	15200	7,600	45,600
dv_{17} (Taylors Lake)	16,850	20,220	10110	26960	26,960	10,110
dv_{18} (Rocklands Reservoir)	208,800	348,000	278400	34800	208,800	34,800
dv_{19} (Lake Lonsdale - via outlet)	52,000	52,000	58500	32500	52,000	65,000
dv_{20} (Moora Moora Reservoir)	5,040	3,150	5040	6300	1,260	1,260
Total	325,619	486,428	387,379	189,704	315,106	202,985
Sustainability Index (SI)	*0.47*	*0.46*	*0.44*	*0.26*	*0.22*	*0.11*

dv_{15} is not included as it alone does not represent a storage maximum operating volume

It is also worth highlighting that Plan no. 5 and Plan no. 3 have greater total maximum operating volumes than that under Plan no. 6. This suggests that increasing the total maximum operating volume too high may have the effect of harvesting too much water and not allowing high fresh flows to satisfy environmental water demands downstream.

4.2.3 Conclusions

Section 4.2 presented a lower order MOOP for the purposes of demonstrating the effectiveness of the SI in terms of ranking optimal operating plans. The outcomes of this analysis are summarised as follows:

- The SI was shown to be a useful tool for evaluating and comparing optimal operating plans with respect to the objective space and decision space. In terms of the objective space, ranking and plotting the SI against its normalised rank provided a visual representation of the Pareto front. For the lower order MOOP discussed, Plan no. 6 was the highest ranked SI operating plan ($SI = 0.47$) and Plan no. 2 was the lowest ranked SI operating plan ($SI = 0.11$). In terms of the decision space, the corresponding decision variable values were plotted together with the SI curve and shown to inform the DM about how different planning decisions influence a system's sustainability.

- The gradient of the SI curve was shown to represent the diversity of the operating plans with respect to the objective space. For the lower order MOOP, the gradient of the curve between Plan no. 3 and Plan no. 1 was greater than that given between Plan no. 1 and Plan no. 4. It was shown that the average of the crowding distances for Plan no. 3 and Plan no. 1 was greater than that given by Plan no. 1 and Plan no. 4. Thus, the gradient of the SI curve provided the DM with a sense of the diversity amongst the optimal operating plans along the Pareto front.

It is important to mention that the lower order MOOP assumes that the sustainability of the WGWSS can be quantified in terms of environmental interests only, and as such ignores the implications of changes to the maximum operating volumes with respect to non-environmental interests for water. This may cause the O-S model to find optimal operating plans that have detrimental effects on other water users such as those identified in this work (e.g. the significant reductions in maximum operating volume at Lake Bellfield which would in all likelihood affect the supply to consumptive users via the Wimmera Mallee Pipeline). This highlights the importance of problem formulation and the need to take explicit account for all interests for water in order for the optimal operating plans to be relevant in a real-world sense. Nonetheless, the outcomes of this work demonstrate that the SI provides a convenient and simple means to rank optimal operating plans with respect to many objectives and many optimal operating plans as generally occurs in higher order MOOPs.

4.3 A series of higher order MOOPs – all user groups

The purpose of this section is to demonstrate the effectiveness of the SI as a means to assess the level of influence a set of operating rules has on the sustainability of the WGWSS. By understanding which planning decisions underpin the sustainability of the system, the DM is aware of which operating rules are paramount in terms of the overall operating plan. This information would be particularly useful in water resources systems that have many complex operating rules which must be optimised in order to maintain an agreed level of sustainability or to improve on current levels. This section builds on the analysis of the lower order MOOP discussed in Section 4.2 which showed that the SI could be used to rank optimal operating plans. The same principles developed for that problem are applied to a series of higher order MOOPs which consider the needs of all user groups in the WGWSS. Each O-S model run within the series focuses on one group of planning decisions as defined by the six categories given in Table 4.1. Run (A1), the higher order MOOP described in Section 3.3, is also included in this analysis as it serves as a basis from which to evaluate each O-S model run.

4.3.1 Problem formulation and model setup

The problem is to optimise the system operating rules with regards to 18 competing objectives which consider environmental, social, consumptive, and system-wide interests for water - refer to Equations 4.9 to 4.26. As explained in Section 3.3, the problem is formulated based on the assumption that the sustainability of the WGWSS is measured in terms of three performance metrics (i.e. reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i)) for the i^{th} interest for water. Equations 4.9 to 4.11 relate to three environmental (env) interests for water expressed in terms of nil environmental flow deficits, and are the same as Equations 4.6 to 4.8 in Section 4.2.1. Equations 4.12 to 4.20 relate to nine social ($socio$) interests for water expressed in terms of the volume of the j^{th} storage (S_j) being Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR). Equations 4.21 to 4.23 relate to three consumptive ($cons$) interests for water expressed in terms of nil supply deficits. Equations 4.24 to 4.26 relate to three system-wide interests for water expressed in terms of water allocations ($alloc$). The 18 objective functions are in direct conflict with each other both between the various interests for water and within each interest for water. For instance, increasing the performance of the environmental objectives means that there is less water extracted from waterways which reduces the volume available for supply to consumptive users and for provision of recreation amenity, and vice versa. Additionally, within the environmental user group, an increase the reliability of nil environmental flow deficits does not necessarily equate to an increase in resiliency; nor does the increase in any or both of these two objectives (i.e. reliability and resiliency) result in reduced vulnerability of such deficits, and vice versa.

$$\text{Maximise}, f_1 = Rel_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0}{n}, \text{where } n = 118 \text{ years} \quad (4.9)$$

$$\text{Maximise}, f_2 = Res_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{env,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occured}} \quad (4.10)$$

$$\text{Minimise}, f_3 = Vul_{env} = \frac{(\sum_{t=1}^{12} Def_{env,t})/\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{env,t})} \quad (4.11)$$

$$\text{Maximise}, f_4 = Rel_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (4.12)$$

$$\text{Maximise}, f_5 = Res_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML follows } S_{LL,t} \le 5{,}379 \text{ ML}}{\text{No. of months } S_{LL,t} \le 5{,}379 \text{ ML occured}} \quad (4.13)$$

$$\text{Minimise}, f_6 = Vul_{LL} = \frac{(\sum[\max\{0,(5{,}379 \text{ ML} - S_{LL,t})\}]/\text{No. of months } S_{LL,t} \le 5{,}379 \text{ ML occurred}}{\text{Average of } S_{LL,t}} \quad (4.14)$$

$$\text{Maximise}, f_7 = Rel_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (4.15)$$

$$\text{Maximise}, f_8 = Res_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML follows } S_{LF,t} \le 1{,}761 \text{ ML}}{\text{No. of months } S_{LF,t} \le 1{,}761 \text{ ML occured}} \quad (4.16)$$

$$\text{Minimise}, f_9 = Vul_{LF} \quad \frac{(\sum[\max\{0,(1{,}761 \text{ ML} - S_{LF,t})\}]/\text{No. of months } S_{LF,t} \le 1{,}761 \text{ ML occurred}}{\text{Average of } S_{LF,t}} \quad (4.17)$$

$$\text{Maximise}, f_{10} = Rel_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML}}{n}, \text{ where } n = 1{,}416 \text{ months} \quad (4.18)$$

$$\text{Maximise}, f_{11} = Res_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML follows } S_{RR,t} \le 69{,}600 \text{ ML}}{\text{No. of months } S_{RR,t} \le 69{,}600 \text{ ML occured}} \quad (4.19)$$

$$\text{Minimise}, f_{12} = Vul_{RR} = \frac{(\sum[\max\{0,(69{,}600 \text{ ML} - S_{RR,t})\}]/\text{No. of months } S_{RR,t} \le 69{,}600 \text{ ML occurred}}{\text{Average of } S_{RR,t}} \quad (4.20)$$

$$\text{Maximise}, f_{13} = Rel_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0}{n}, \text{ where } n = 118 \text{ years} \quad (4.21)$$

$$\text{Maximise}, f_{14} = Res_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{cons,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occured}} \quad (4.22)$$

$$\text{Minimise}, f_{15} = Vul_{cons} = \frac{(\sum_{t=1}^{12} Def_{cons,t})/\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{cons,t})} \quad (4.23)$$

$$\text{Maximise}, f_{16} = Rel_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML}}{n}, \text{ where } n = 118 \text{ years} \quad (4.24)$$

$$\text{Maximise}, f_{17} = Res_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML follows } W_{system,June} < 97{,}550 \text{ ML}}{\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}} \quad (4.25)$$

$$\text{Minimise}, f_{18} = Vul_{alloc} = \frac{(\sum(97{,}550 \text{ ML} - W_{system,June})/\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}}{\text{Average of } W_{system,June}} \quad (4.26)$$

Where, t = July, August, September, … … . , June;

Subject to the constraints as configured in the revised Wimmera-Glenelg REALM model (refer Section 3.3.2).

The decision variables to solve for are dv_1 to dv_{24} as specified in Table 4.1.

The above higher order MOOPs are solved for five generations using the O-S modelling approach with the following optimisation parameters: $\text{population size (N)} = 100,\ \text{probability of crossover } (p_c) = 0.8, \text{and probability of mutation } (p_m) = 0.2$ (refer Section 3.4.2.2 for further details regarding the optimisation parameters adopted).

In order to assess the level of influence a set of operating rules has on the sustainability of the WGWSS, the 18-objective problem is used to solve for one planning decision category at a time. The 24 planning decisions are categorised into 6 different areas of system operation related to priorities of supply; storage flood reserve volumes; environmental allocation shares; flow paths; storage maximum operating volumes; and storage draw down priorities and storage targets (refer Table 4.1). The approach used to solve for a single planning decision category is based on the assumption that the DM is interested in improving the current level of sustainability that is achieved under the base case scenario (BC01) by optimising a planning decision category. For this reason, the approach involves setting or *fixing* the decision variables, for all but one of the categories, to the values used in BC01. In this way, the problem is solved for the planning decisions that are not fixed i.e. the O-S model is able to search for optimal operating plans with respect to that (single) set of operating rules only. Table 4.5 sets out the O-S modelling runs undertaken as part of this investigation showing which categories are fixed/not fixed to BC01 levels, denoted with “F” and “NF” respectively. With the exception of Run (A1), this approach results in 6 runs (i.e. Run (B1) to Run (G1)) which are similar to BC01 in all but one facet of system operation. Run (A1) does not have any planning decisions fixed which means that the O-S model is able to search for optimal operating plans with respect to all the operating rules (as per the MOOP described in Section 3.3). In essence, BC01 represents the current operating regime based on past operational experience, whereas the optimal operating plans found under Run (A1) represent the possibility of new operating rules that achieve a greater level of sustainability for the WGWSS.

Table 4.5 Settings of decision variables for optimisation-simulation modelling scenarios Run (A1) to Run (G1)

Category of decision variable	Optimisation-simulation scenarios (**bold**) and corresponding setting of decision variables (F = fixed, NF = not fixed)						
	Run (A1)	**Run (B1)**	**Run (C1)**	**Run (D1)**	**Run (E1)**	**Run (F1)**	**Run (G1)**
Priority of supply (dv_1 to dv_7)	NF	NF	F	F	F	F	F
Flood reserve volume (dv_8)	NF	F	NF	F	F	F	F
Share of environmental allocation (dv_9 to dv_{11})	NF	F	F	NF	F	F	F
Flow path (dv_{12} and dv_{13})	NF	F	F	F	NF	F	F
Storage maximum operating volume (dv_{14} to dv_{20})	NF	F	F	F	F	NF	F
Storage draw down priority and storage target (dv_{21} to dv_{24})	NF	F	F	F	F	F	NF

'NF' refers to decision variables values which are not fixed to those under base case scenario (BC01).
'F' refers to decision variables values which are fixed to those under base case scenario (BC01).

4.3.2 Modelling results and discussion

4.3.2.1 Objective space

For each of the modelling scenarios described in Table 4.5 (i.e. Run (A1) to Run (G1)), the O-S model was run for five generations as for the lower order MOOP (refer to Section 4.2) and the population with the highest ranked SI operating plan was selected for analysis. The O-S model found 56, 29, 49, 48, 6, 49, and 49 optimal operating plans forming the Pareto front for each of the seven scenarios from Run (A1) to Run (G1) respectively. As shown in Section 4.2, the visualisation of the Pareto front is relatively simple in lower order MOOPs whereas for the present higher order MOOP, using a two-dimensional Cartesian coordinate plane would be a tedious exercise resulting in 153 different combinations (C) of the 18 objective functions considered i.e. ${}^{18}C_2 = \frac{18!}{(18-2)!2!} = 153$. However, Figure 4.14 demonstrates the convenience of summarising the optimal operating plans using the SI curve for the seven modelling scenarios. Based on the outcomes of the lower order MOOP, the gradient of the SI curve represents the diversity of the operating plans with respect to the objective space. A larger gradient represents operating plans which are more diverse than those that produce a section of curve with a smaller gradient. The curves in Figure 4.14

show that the optimal operating plans found under Run (F1) provide the greatest diversity amongst plans along the Pareto front, particularly for those 25% of optimal plans between the normalised rank values of 0.15 and 0.4. Note that Run (F1) corresponds to the O-S modelling run that was solved for the storage maximum operating volume category (refer to Table 4.5). Moreover as the SI curve for Run (F1) is in close alignment to the curve produced by the optimal plans under Run (A1), this suggests that the storage maximum operating volumes may be the most influential of all the planning decision categories with respect to the level of sustainability that can be achieved by the WGWSS. Section 4.3.2.2 undertakes an analysis in terms of the decision space with the aim of finding the reason(s) for the close alignment in curves and as to whether this supports the notion that the storage maximum operating volumes are indeed the most influential of all the planning decision categories.

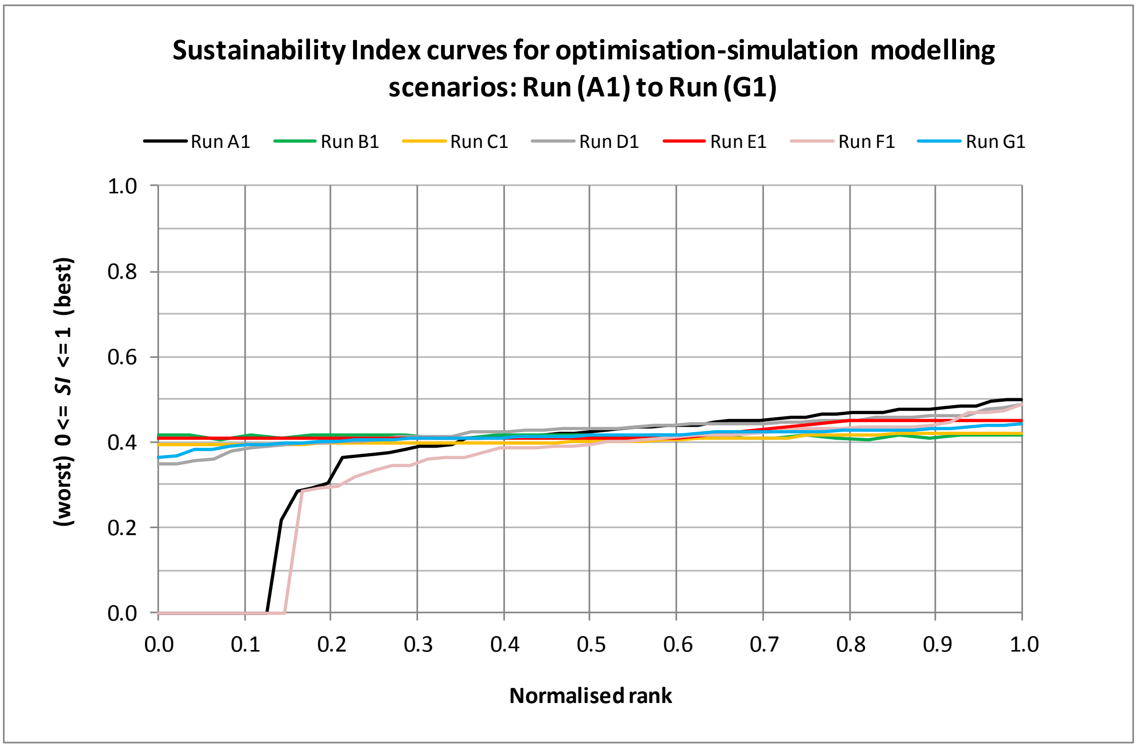


Figure 4.14 Sustainability Index curves for optimisation-simulation modelling scenarios: Run (A1) to Run (G1)

4.3.2.2 <u>Decision space</u>

Following on from the notion that the storage maximum operating volumes may be the most influential of all the planning decision categories (see Section 4.3.2.1), the analysis of the O-S modelling results focuses on the values of dv_{14} to dv_{20} with the aim of finding conclusive evidence that the storage maximum operating volumes are the most influential of all the planning decision categories. The decision variable values (dv_{14} to dv_{20}) for all 49 optimal operating plans under Run (F1) are compared to the values of the 56 optimal plans under Run (A1) using their corresponding SI curve.

Figure 4.15 shows the values for decision variable dv_{18} for all optimal operating plans together with their corresponding SI curve under Run (A1) and Run (F1) respectively. Whilst Figure 4.15 provides a means to investigate the effect of a decision variable value on the sustainability of the system (in terms of SI), these figures do not provide a direct comparison of the distribution of values for all optimal operating plans under Run (A1) and Run (F1). The distribution of values here refers to the number of decision variable values that pertain to a particular class within the range of the decision variable. Understanding the distribution of decision variable values informs the DM of how such values contribute to higher levels of sustainability of the WGWSS. For this purpose, the *relative frequency distribution* of the decision variable values can be used to bring both sets of data together.

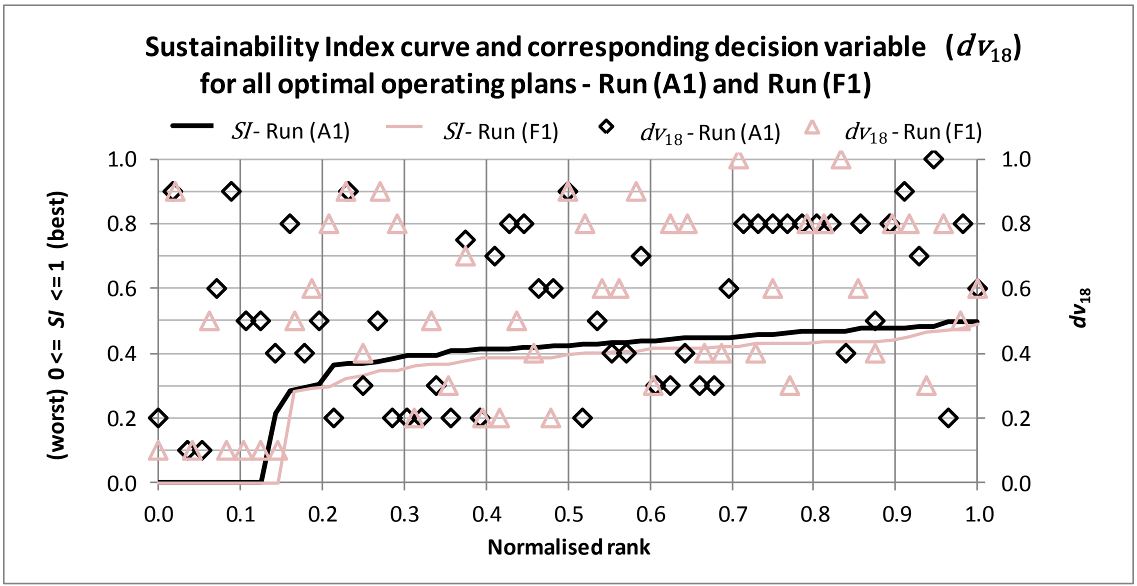


Figure 4.15 Sustainability Index curve and corresponding decision variable (dv_{18}) for maximum operating volume at Rocklands Reservoir - Run (A1) and Run (F1)

The relative frequency in this case is defined as the number of decision variable values that pertain to a particular class within the range of the decision variable divided by the total number of decision variables in the whole range. For instance, Figure 4.15 shows that there are 2 out of 56 optimal operating plans under Run (A1) which have a dv_{18} value of 0.1 (i.e. $\frac{2}{56} = 3.6\%$). Figure 4.16 shows the relative frequency distribution of decision variable dv_{18} under both Run (A1) and Run (F1). It also shows that the largest disparity in dv_{18} occurs for values 0.1 and 0.2. Figure 4.15 shows that a value of 0.2 in dv_{18} generally has the effect of contributing to an increase in the SI whereas a value of 0.1 has the opposite effect.

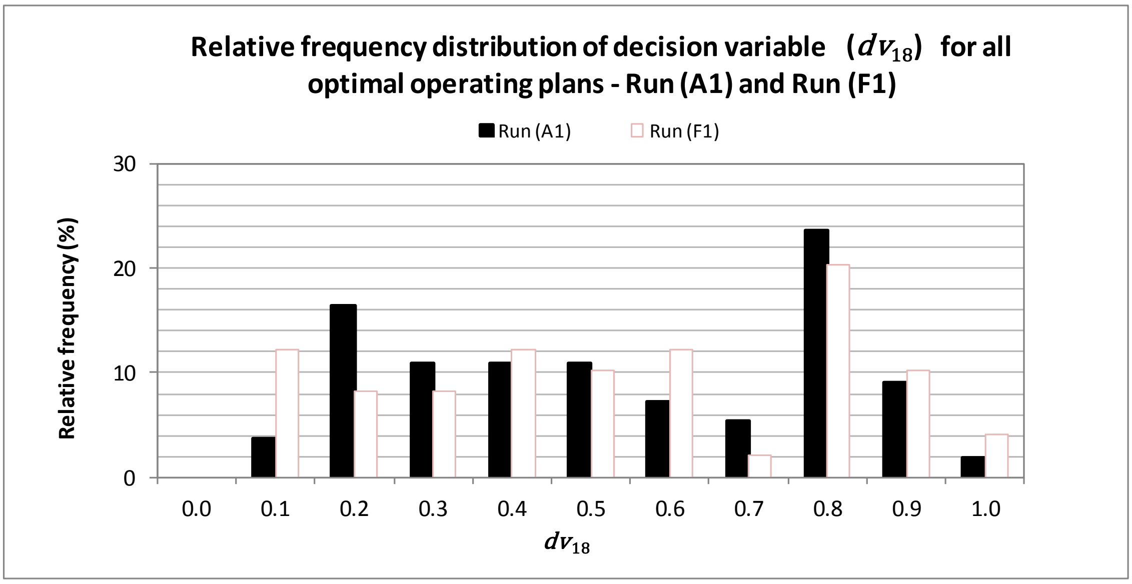


Figure 4.16 Relative frequency distribution of decision variable (dv_{18}) maximum operating volume at Rocklands Reservoir - Run (A1) and Run (F1)

The remaining storage maximum operating volumes (i.e. dv_{14} to dv_{17}, dv_{19}, and dv_{20}) are analysed in the same way; by focusing on the largest disparity between corresponding decision variable values under Run (A1) and Run (F1) in order to explain how individual maximum operating volumes contribute to higher levels of sustainability of the WGWSS. In Section 4.2.2.2, the decision variables corresponding to the storage maximum operating volumes for Rocklands Reservoir, Toolondo Reservoir, and Taylors Lake (i.e. dv_{18}, dv_{14}, and dv_{17}) were analysed together as these storages are generally operated as a sub-system of the WGWSS. Toolondo Reservoir is primarily used as a balancing storage in order to maximise the harvesting of flows from the upper Glenelg River at Rocklands Reservoir with transfers to Taylors Lake downstream of Toolondo Reservoir (refer Figure 4.1). Figure 4.17 and Figure 4.18 compare the decision variable values for the storage maximum operating volume for Toolondo Reservoir (i.e. dv_{14}) under Run (A1) and Run (F1) using the SI curve and the relative frequency distribution respectively. The results for Toolondo Reservoir

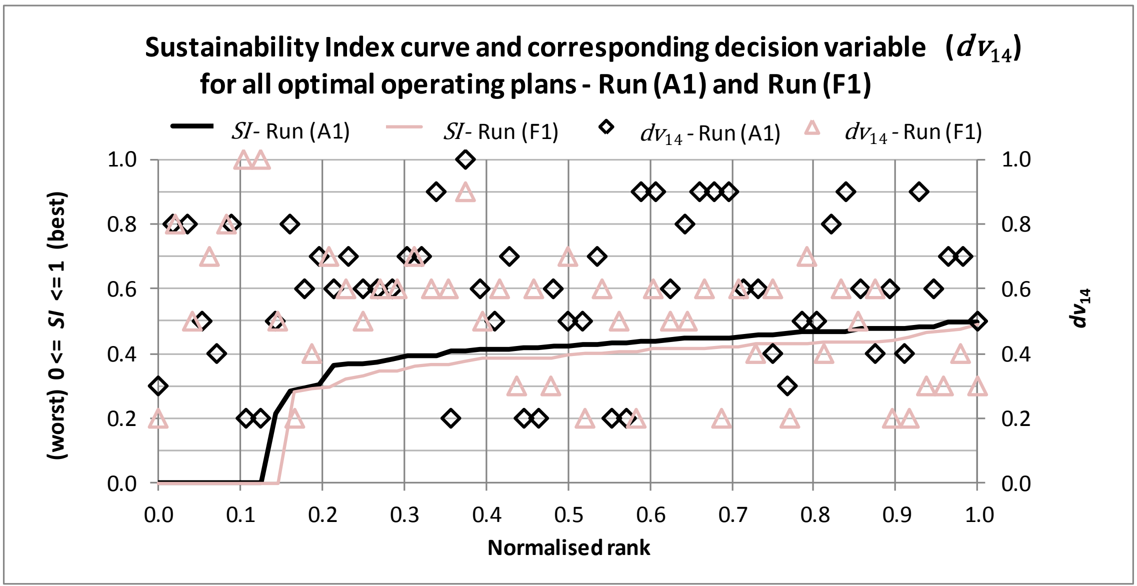


Figure 4.17 Sustainability Index curve and corresponding decision variable (dv_{14}) for maximum operating volume at Toolondo Reservoir - Run (A1) and Run (F1)

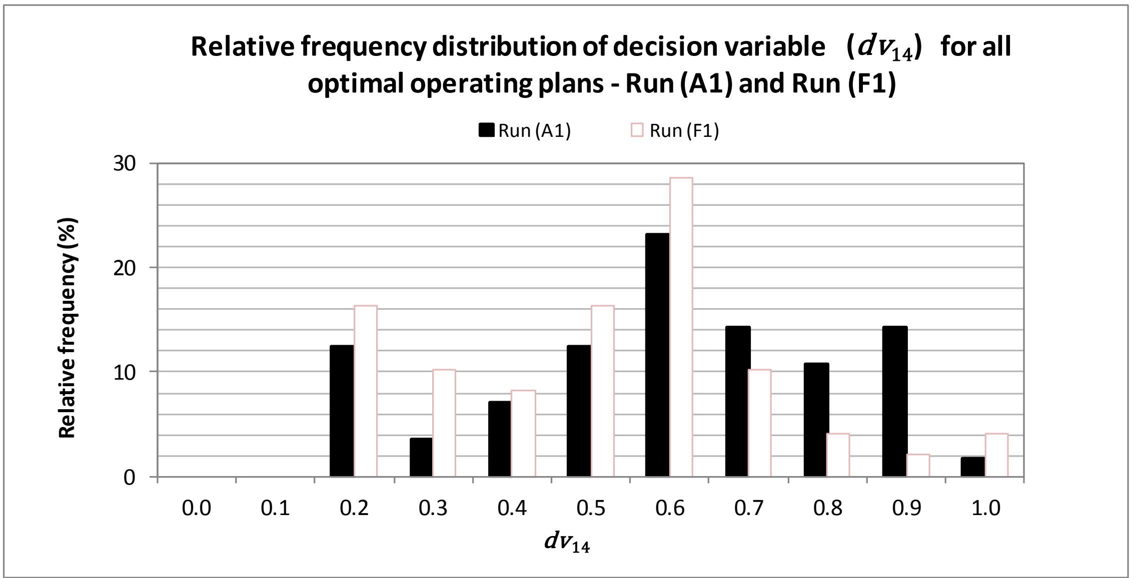


Figure 4.18 Relative frequency distribution of decision variable (dv_{14}) maximum operating volume at Toolondo Reservoir - Run (A1) and Run (F1)

show that the largest disparity in variable value is for $dv_{14} = 0.9$, where this value is used in eight optimal operating plans under Run (A1) and in one optimal plan under Run (F1). In general, the results show that optimal operating plans that have a dv_{14} value of 0.9 contribute to higher levels of sustainability for the WGWSS. Figure 4.19 and Figure 4.20 compare the decision variable values for Taylors Lake (i.e. dv_{17}) using

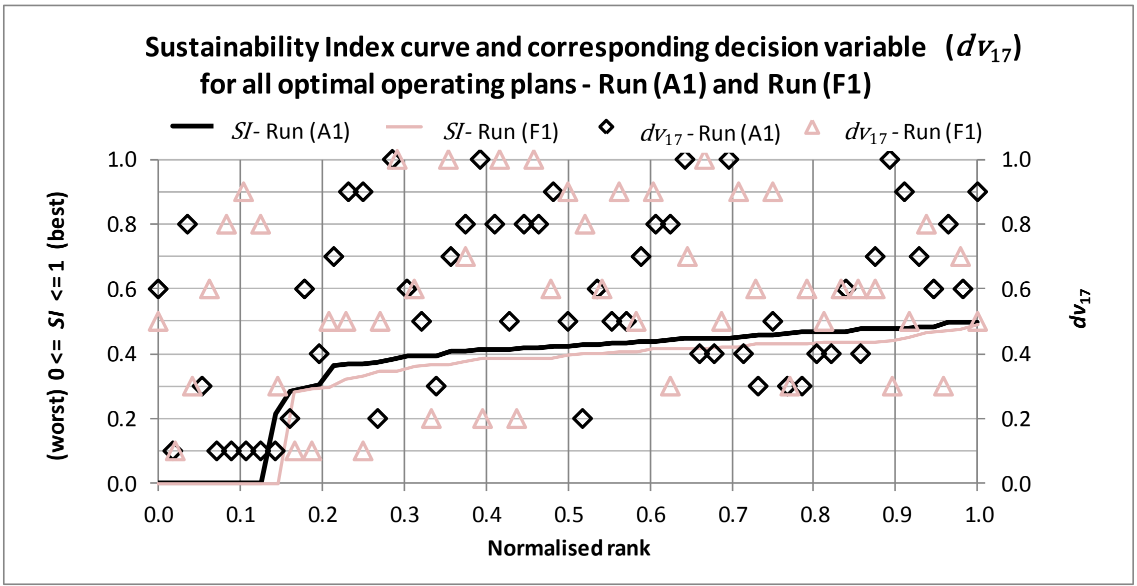


Figure 4.19 **Sustainability Index curve and corresponding decision variable (dv_{17}) for maximum operating volume at Taylors Lake - Run (A1) and Run (F1)**

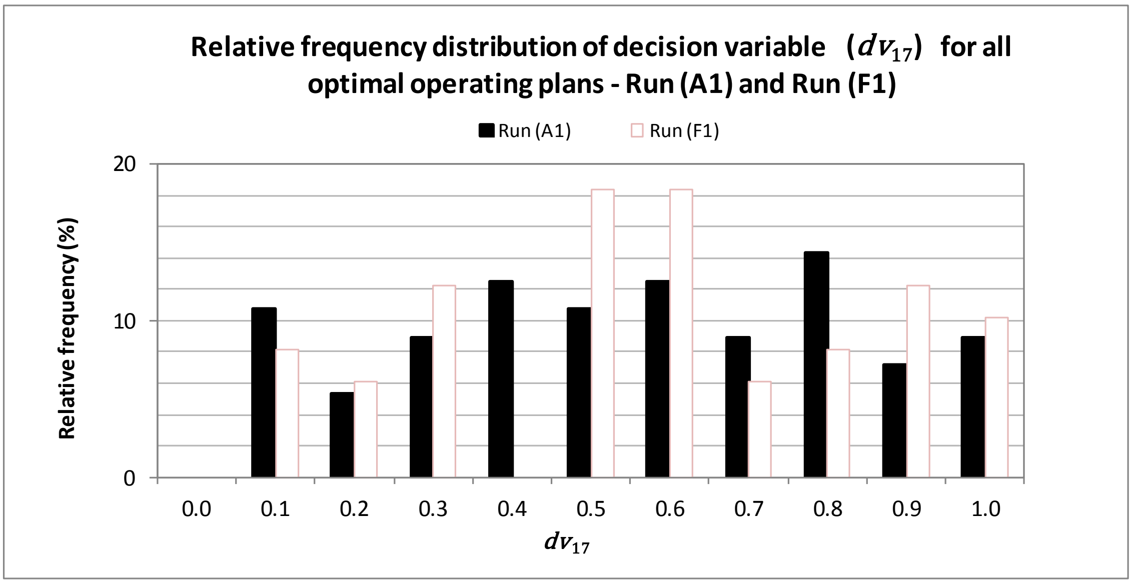


Figure 4.20 **Relative frequency distribution of decision variable (dv_{17}) maximum operating volume at Taylors Lake - Run (A1) and Run (F1)**

the SI curve and the relative frequency distribution respectively. The results for Taylors Lake show that the largest disparity in variable value is for $dv_{17} = 0.4$, where this value is used in seven optimal operating plans under Run (A1) and in none of the optimal plans under Run (F1). In general, the results show that optimal operating plans that use a dv_{17} value of 0.4 contribute to an increase in the sustainability level of the WGWSS.

Overall, the results for Rocklands Reservoir, Toolondo Reservoir, and Taylors Lake indicate that higher values of the corresponding decision variables contribute to higher levels of sustainability of the WGWSS.

Lake Bellfield is the primary source of supply to consumptive users (19) to (30) and is operated at FSV except over the April to September period when it is lowered to 97% of FSV for dam safety reasons and to manage flood flows (see Figure 4.1). Figure 4.21 and Figure 4.22 compare the decision variable values for the storage maximum operating volume for Lake Bellfield (i.e. dv_{16}) using the SI curve and the relative frequency distribution respectively. The results show that the disparity in dv_{16} is relatively uniform across all values and that there is no obvious pattern in terms of how certain values of this decision variable contribute to higher levels of sustainability of the WGWSS.

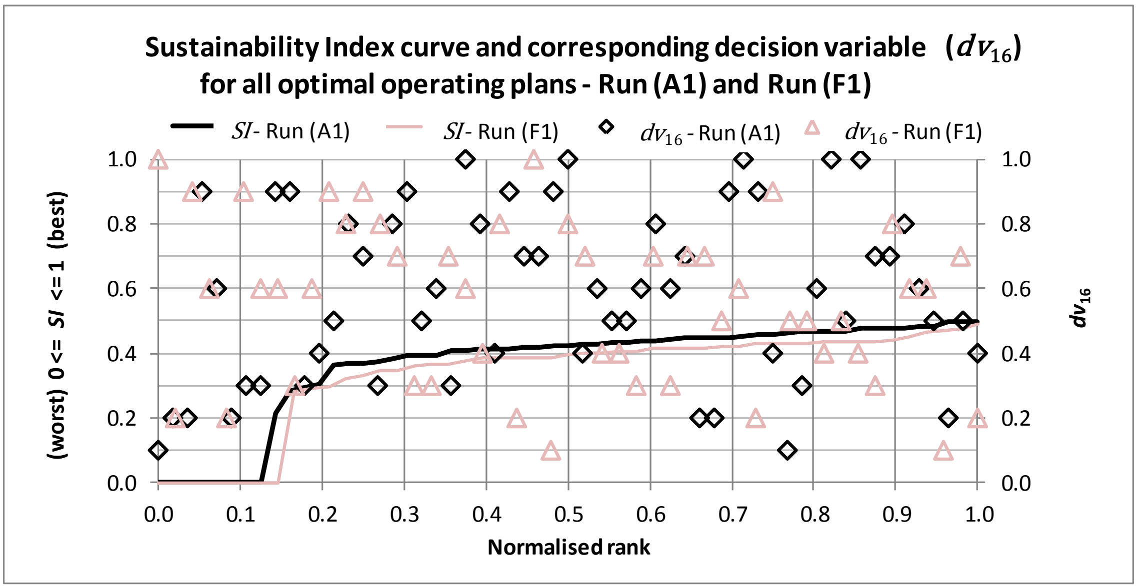


Figure 4.21 Sustainability Index curve and corresponding decision variable (dv_{16}) for maximum operating volume at Lake Bellfield - Run (A1) and Run (F1)

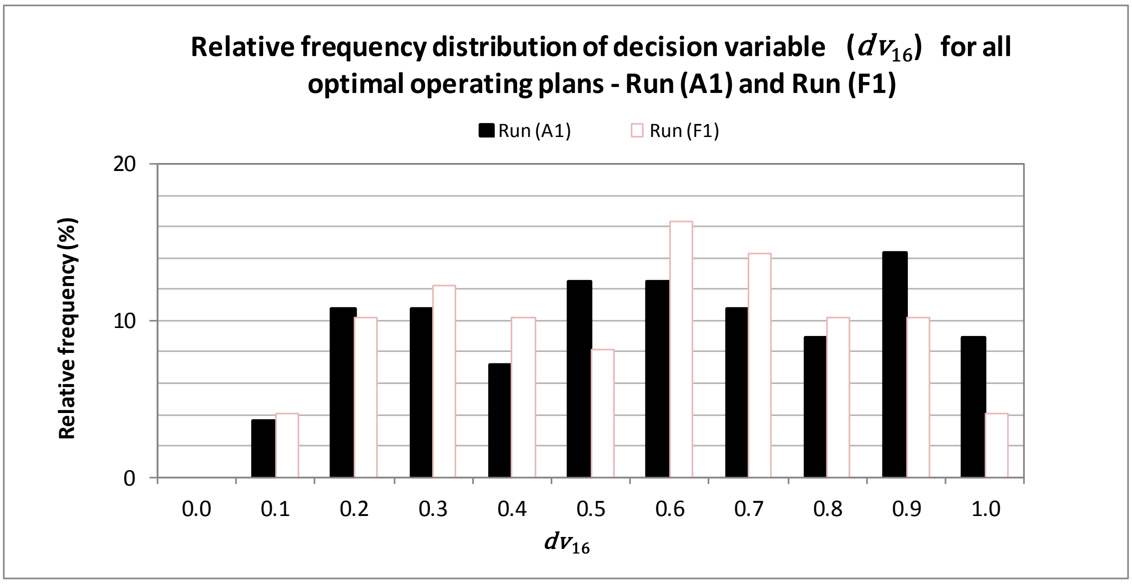


Figure 4.22 Relative frequency distribution of decision variable (dv_{16}) maximum operating volume at Lake Bellfield - Run (A1) and Run (F1)

As explained in Section 4.2.2.2, there are two decision variables that control the maximum operating volume at Lake Lonsdale. Decision variable dv_{15} controls the flow of water entering the storage and has a value of either 0 or 1, where 0 means that the inlet is completely closed and 1 represents a fully opened inlet. Decision variable dv_{19} controls the storage operating volume and has a value between 0 and 1, where 0 means that the storage is effectively not used or decommissioned and 1 represents a maximum operating volume at FSV.

Figure 4.23 and Figure 4.24 compare the decision variable values for the inlet at Lake Lonsdale (i.e. dv_{15}) using the SI curve and the relative frequency distribution respectively. The results for the inlet show that there are more optimal operating plans that use a value of 0 for dv_{15} under Run (A1) than those under Run (F1). That is, a greater number of optimal operating plans use values of 0.1, 0.3, 0.4, 0.5, and 0.6 under Run (A1) compared to those under Run (F1). The results for both decision variables (dv_{15} and dv_{19}) indicate that values which represent a closed inlet together with lower maximum operating volumes contribute to higher levels of sustainability of the WGWSS.

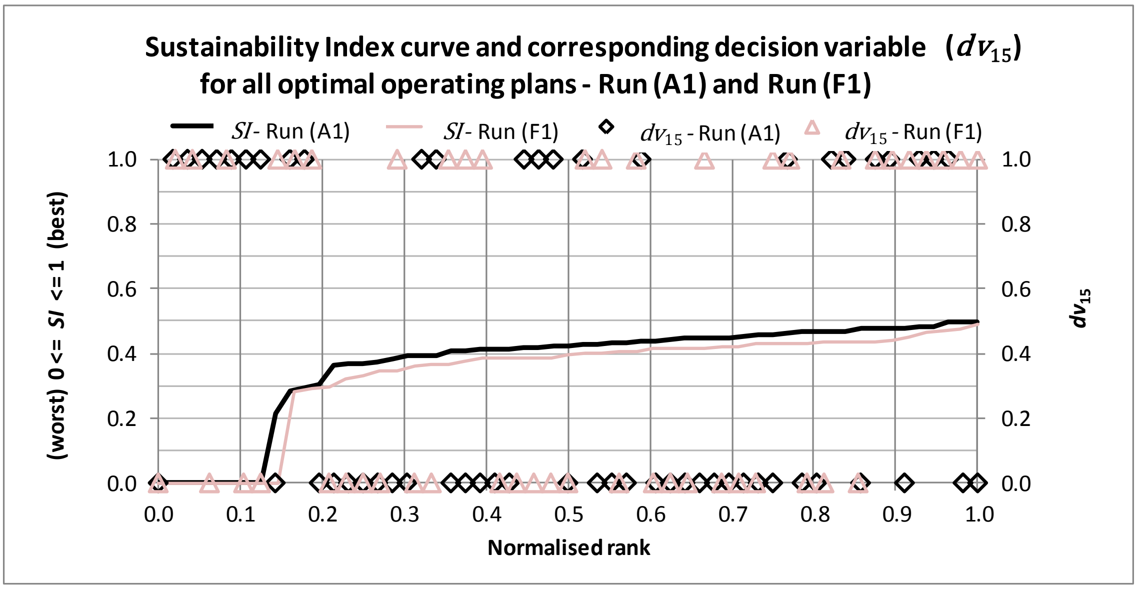


Figure 4.23 **Sustainability Index curve and corresponding decision variable (dv_{15}) for maximum operating volume at Lake Lonsdale (inlet) - Run (A1) and Run (F1)**

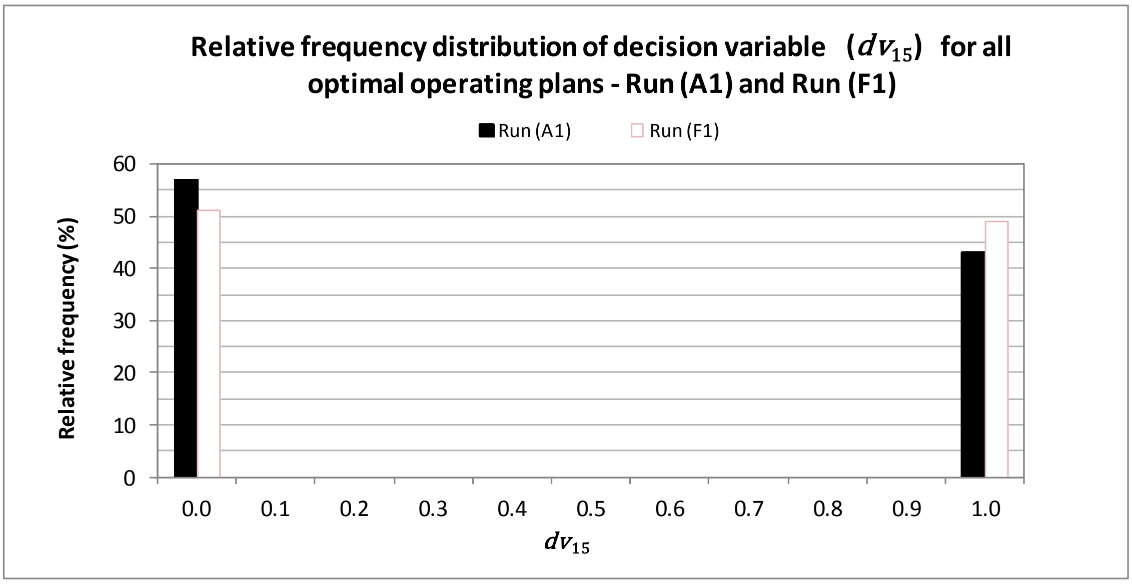


Figure 4.24 **Relative frequency distribution of decision variable (dv_{15}) maximum operating volume at Lake Lonsdale (inlet) - Run (A1) and Run (F1)**

Figure 4.25 and Figure 4.26 compare the decision variable values for the storage maximum operating volume for Lake Lonsdale (i.e. dv_{19}) using the SI curve and the relative frequency distribution respectively. The results generally show that there are more optimal operating plans that use lower values of dv_{19} under Run (A1) than those under Run (F1).

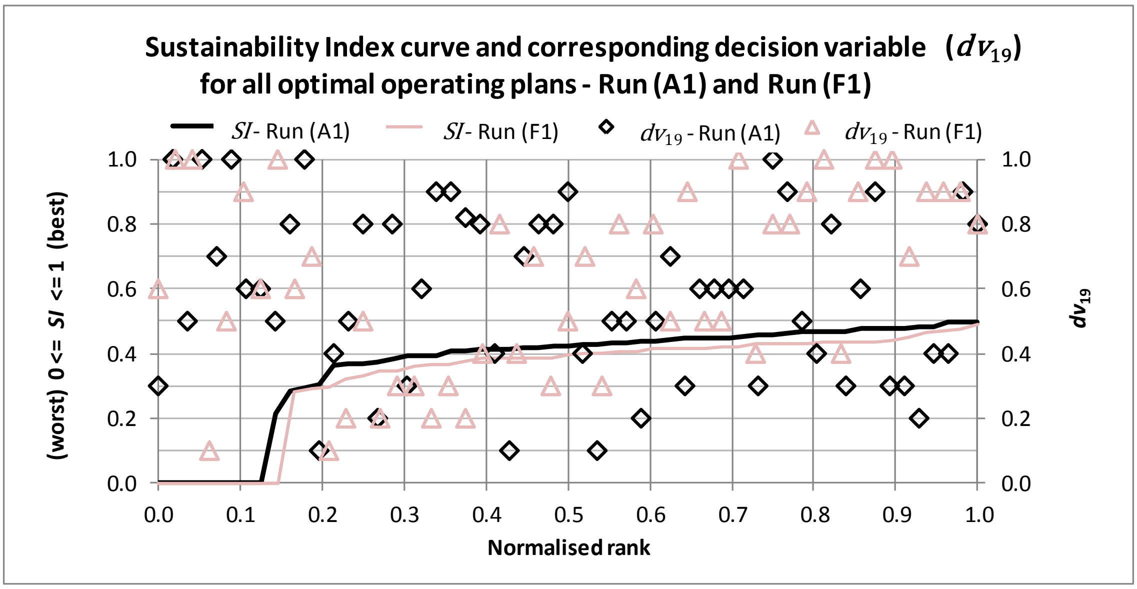


Figure 4.25 Sustainability Index curve and corresponding decision variable (dv_{19}) for maximum operating volume at Lake Lonsdale (outlet) - Run (A1) and Run (F1)

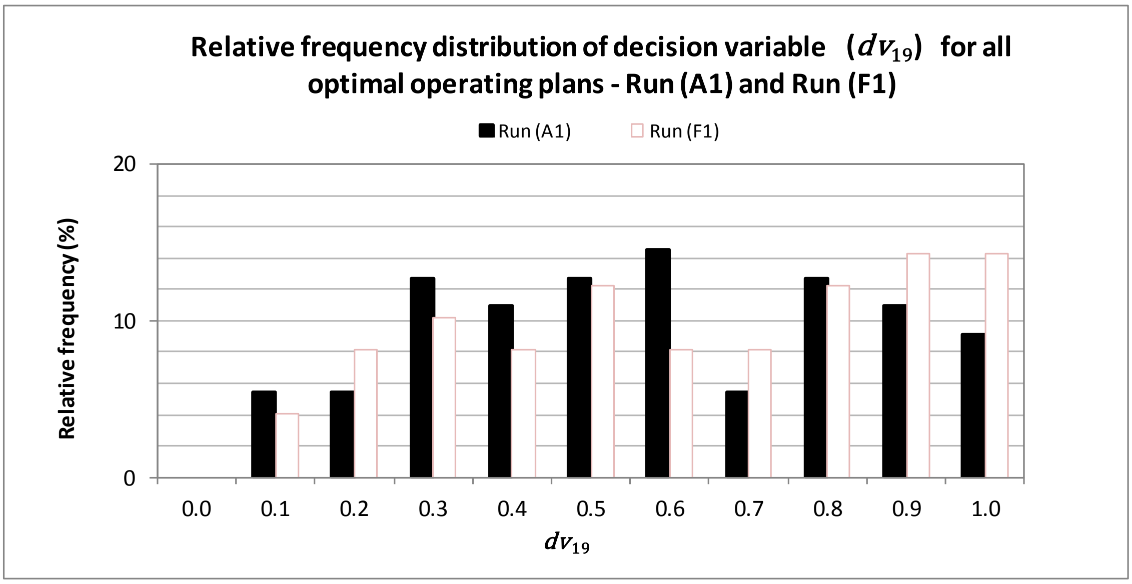


Figure 4.26 Relative frequency distribution of decision variable (dv_{19}) maximum operating volume at Lake Lonsdale (outlet) - Run (A1) and Run (F1)

Figure 4.27 and Figure 4.28 compare the decision variable values for the storage maximum operating volume for Moora Moora Reservoir (i.e. dv_{20}) using the SI curve and the relative frequency distribution respectively. The results show that the disparity in the two runs in dv_{20} is relatively uniform across all values and that there is no obvious pattern in terms of how certain values of this decision variable contribute to

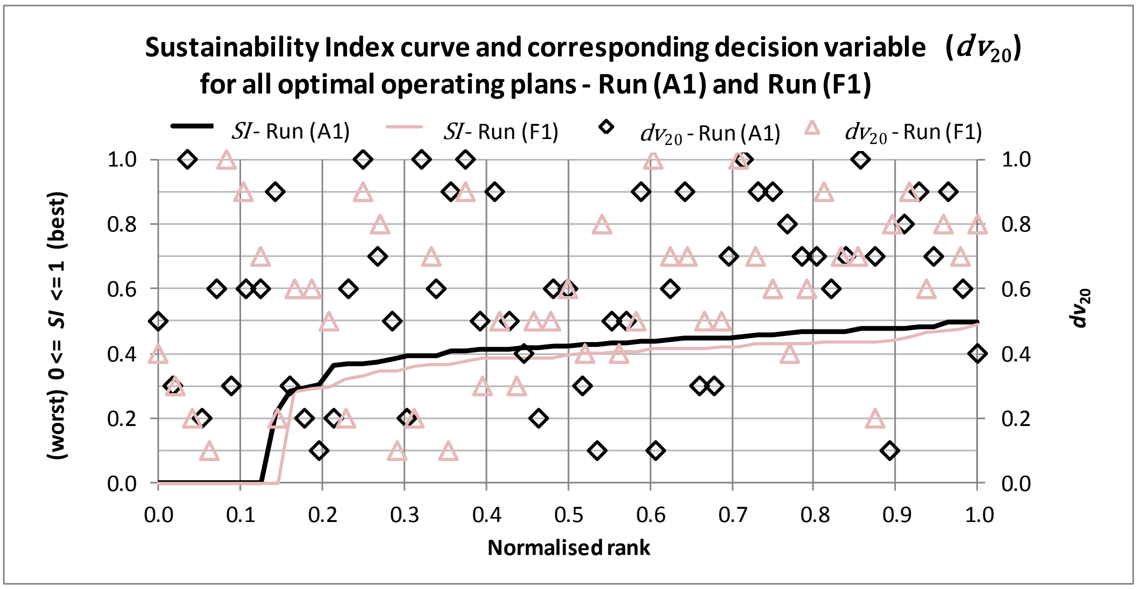


Figure 4.27 **Sustainability Index curve and corresponding decision variable (dv_{20}) for maximum operating volume at Moora Moora Reservoir - Run (A1) and Run (F1)**

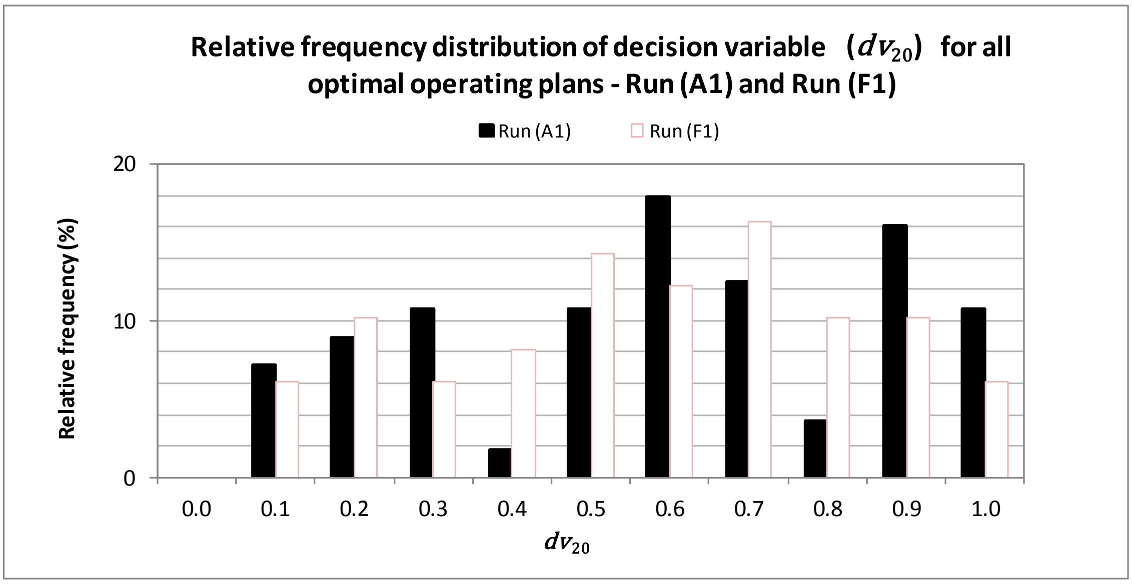


Figure 4.28 **Relative frequency distribution of decision variable (dv_{20}) maximum operating volume at Moora Moora Reservoir - Run (A1) and Run (F1)**

higher levels of sustainability of the WGWSS.

4.3.2.3 Discussion

The results presented in Sections 4.3.2.1 and 4.3.2.2 show that the effect of decision variables dv_{14} to dv_{20} is varied with respect to their effect on the sustainability of the WGWSS (in terms of SI). For instance, the combined effect of higher storage maximum operating volumes for Rocklands Reservoir, Toolondo Reservoir, and Taylors Lake contribute to higher levels of sustainability (i.e. dv_{18} , dv_{14} , and dv_{17}). Interestingly the combined effect of decision variables for Lake Lonsdale (i.e. dv_{15} and dv_{19}) show that there is an increase in the system's sustainability with the inlet completely closed together with a decrease in the maximum operating volume. Both sets of results indicate that the O-S model has found optimal operating plans that balance the harvesting of water and the needs of users between the storages located in western parts of the WGWSS (i.e. Rocklands Reservoir, Toolondo Reservoir and Taylors Lake) and those in the eastern parts (i.e. Lake Lonsdale and to a lesser extent Lake Bellfield). This balancing approach is a feature of the current operating regime as it has worked successfully since 1966 when the last headworks storage, Lake Bellfield, was completed (Barlow, 1987; GWMWater, 2011).

The results for Lake Bellfield and Moora Moora Reservoir showed that there were no obvious patterns for how certain values of the corresponding decision variables contributed to higher levels of system sustainability (i.e. dv_{16} and dv_{20}). Such results suggest that the DM would have a greater degree of flexibility in terms of the operation of Lake Bellfield and Moora Moora Reservoir with respect to maintaining/improving the sustainability of the WGWSS. This flexibility would benefit all users, particularly in the case of Lake Bellfield which is currently the primary source of supply to consumptive users (19) to (30) (refer Figure 4.1) and is also a popular tourist destination given its recreation amenity (e.g. fishing, boating, camping etc). However the current practice is to operate Lake Bellfield at FSV except over the April to September period when it is lowered to 97% of FSV for dam safety reasons and to manage flood flows. The reason for this is to ensure that the consumptive users receive an acceptable level of water quality which is often better at Lake Bellfield than that downstream at Lake Lonsdale and Taylors Lake. As such water quality considerations have not been included in the MOOP as an objective function (for Lake Bellfield), it is suggested that any major changes to the storage maximum operating volume for Lake Bellfield be further investigated in terms of the effect that different sources of water have on supplies to the consumptive users.

In a similar discussion to that for the lower order MOOP in Section 4.2.2.3, the results of the higher order MOOP may also be discussed in terms of the sum of the individual storage maximum operating volumes for Toolondo Reservoir, Lake Bellfield, Taylors Lake, Rocklands Reservoir, Lake Lonsdale, and Moora Moora Reservoir. Figure 4.29 compares the total maximum operating volumes for all optimal operating plans under Run (A1) and Run (F1) using the *SI* curve. The results for both runs show that higher total maximum operating volumes generally contribute to higher levels of sustainability of the WGWSS. Note that this outcome is the same as that for the lower order MOOP which considered three environmental objectives.

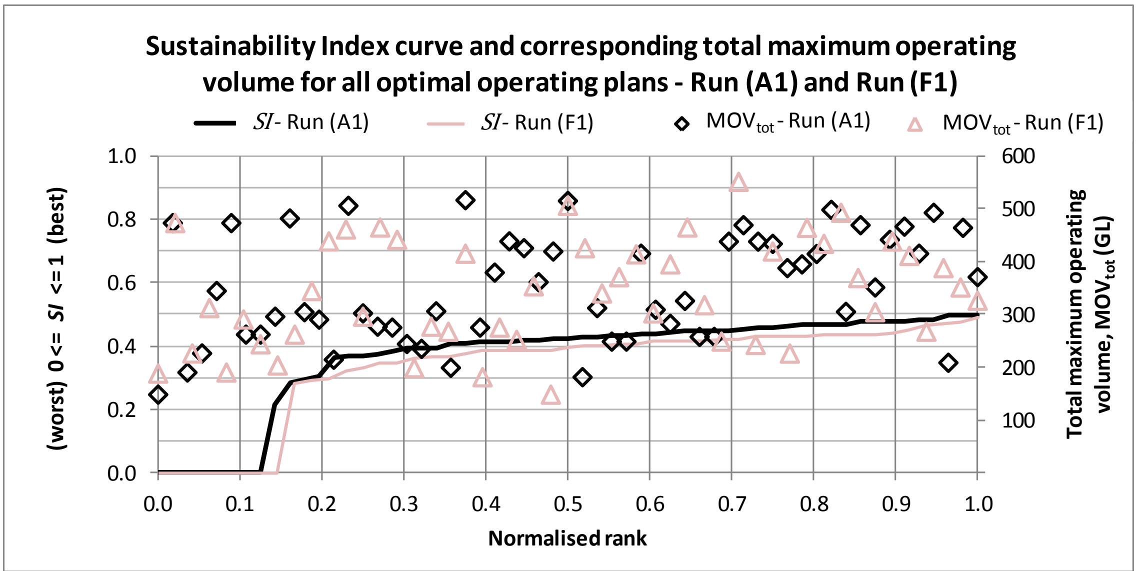


Figure 4.29 **Sustainability Index curve and corresponding total maximum operating volume for all optimal operating plans - Run (A1) and Run (F1)**

Figure 4.30 compares the total maximum operating volumes for all optimal operating plans under Run (A1) and Run (F1) in terms of their relative frequency distribution. With respect to the 100 GL class interval considered, the results show that the relative frequency distribution of total maximum operating volumes between both runs is relatively uniform. This means that both runs have very similar optimal operating plans in terms of the number of plans that specify a similar total maximum operating volume. This similarity in results together with the close alignment of the *SI* curve for Run (F1) with Run (A1) (refer to Figure 4.14), provides conclusive evidence that the maximum operating volumes are indeed the most influential of all the planning decision categories with respect to the level of sustainability of the WGWSS. Had there instead been a disparity between the relative frequency distribution between both runs, the results would have indicated that there were other operating rules (from at least one other planning decision category) which worked in combination with the storage maximum operating volumes in order to achieve an SI curve in close alignment to Run (A1). This important information means that the DM is able to focus more attention on those operating rules which have the greatest impact on improving or maintaining a desired level of sustainability.

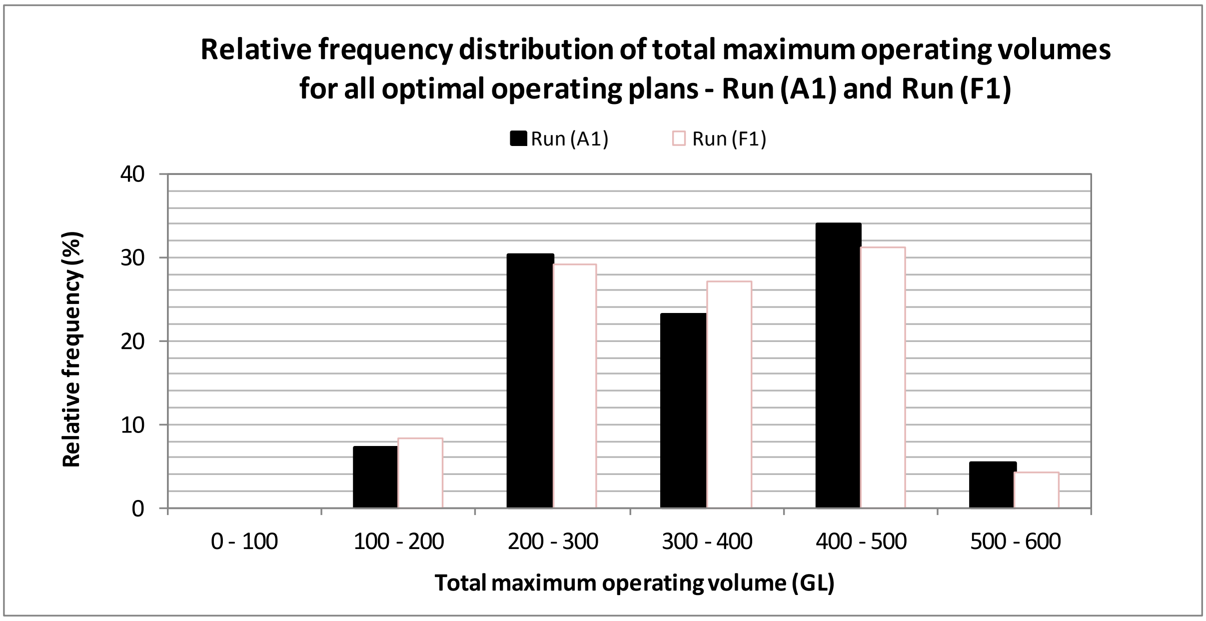


Figure 4.30 Relative frequency distribution of total maximum operating volumes for all optimal operating plans - Run (A1) and Run (F1)

Whilst the results in Figure 4.14 and Figure 4.30 show that the storage maximum operating volumes are the most influential of all the planning decisions considered (in terms of SI), it is important to highlight that this does not mean that the other planning decisions are not as important (as the storage maximum operating volumes). Evidence of this is given by the fact that the SI curve for Run (F1) is not exactly the same as that for Run (A1). This difference means that the other (less influential) planning decisions play a part in contributing to higher levels of sustainability of the WGWSS. It is for this reason, that all planning decisions considered thus far are included in the higher order MOOPs presented in Section 4.4 and Chapter 5.

4.3.3 Conclusions

Section 4.3 presented a higher order MOOP for the purposes of demonstrating the effectiveness of the SI as a means to assess the level of influence a set of operating rules has on the sustainability of the WGWSS. A total of 24 planning decisions were categorised into six different sets of operating rules and the O-S model was run to solve the 18-objective problem, one planning decision category at a time. The six planning decision categories related to priorities of supply (Run B1); storage flood reserve volumes (Run C1); environmental allocation shares (Run D1); flow paths (Run E1); storage maximum operating volumes (Run F1); and storage draw down priorities and storage targets (Run G1) - refer to Table 4.1 for further details. As Run (A1) was used to solve for all six planning decision categories in a single O-S model run, it was used as a point of comparison representing the highest levels of sustainability in terms of SI. The outcomes of this analysis are summarised as follows:

- The SI was shown to be a useful tool for comparing optimal operating plans for multiple modelling scenarios. In the objective space analysis, the SI curve was used to compare the optimal plans found under the seven O-S modelling scenarios on a single chart. The alternative two-dimensional plotting approach would have resulted in 153 different charts each with a total of 286 optimal plans which would have been a tedious task to analyse. Comparing the SI curves against Run (A1), showed that the optimal operating plans found under Run (F1) were in close alignment to Run (A1) and that the plans under Run (F1) were the most diverse of all runs, particularly for those 25% of optimal plans between the normalised rank values of 0.15 and 0.4. Note that Run (F1) relates to the storage maximum operating volumes of Rocklands Reservoir, Toolondo Reservoir, Taylors Lake, Lake Lonsdale, Lake Bellfield, and Moora Moora Reservoir.
- The decision space analysis compared Run (F1) against Run (A1) using the SI curve and the relative frequency distribution of decision variable values. The decision variable values of optimal operating plans under Run (F1) showed that the effect of such values, in terms of the sustainability of the WGWSS, was

varied for the storages considered. The results showed that higher maximum operating volumes for some storages contributed to higher levels of sustainability (e.g. Rocklands Reservoir), while in other cases lower maximum operating volumes had the same effect on sustainability (e.g. Lake Lonsdale).

- The SI was shown to be a useful tool for assessing the influence of operating rules on the sustainability of the WGWSS. This was demonstrated by comparing the results of Run (F1) to Run (A1) in terms of the close alignment of the SI curves and the relative frequency distribution of decision variable values. Together, both sets of results confirmed that the storage maximum operating volumes were the most influential of all the planning decision categories with respect to the level of sustainability of the WGWSS.

Whilst the results showed that the storage maximum operating volumes were the most influential of all the planning decisions considered (in terms of SI), it was pointed out that it did not mean that the other planning decisions were any less important than the storage maximum operating volumes. Evidence of this was given by the fact that the SI curve for Run (F1) was not exactly the same as that for Run (A1). This difference meant that the other (less influential) planning decisions played a part in contributing to higher levels of sustainability of the WGWSS. It was explained that this was the reason for continuing to include all (six) planning decision categories as part of the higher order MOOPs in Section 4.4 and Chapter 5.

Section 4.3 has shown that by understanding which planning decisions underpin the sustainability of the system, the DM is informed of which operating rules are paramount in terms of the overall operating plan. Additionally, higher levels of diversity in the plans along the Pareto front means that the DM has a wider range of optimal plans to choose from should there be a need to modify the current operating plan in order to maintain an agreed level of sustainability or to improve on current levels. It is worth highlighting that such comparative information, in relation to the effect of planning decisions on sustainability levels, is not readily available to the DM at present time. This is particularly important in the WGWSS as the interconnected nature of the headworks means that there is the possibility to develop new, and potentially better, operating plans that increase the sustainability of the system.

4.4 A higher order MOOP for the Wimmera-Glenelg Water Supply System – all user groups

So far the SI has been shown to be a useful tool for analysing optimal operating plans along the Pareto front. In Section 4.2, the SI was used to rank optimal plans for a lower order MOOP. Section 4.3 incorporated the SI in an investigation of various higher order MOOPs in order to assess the level of influence different planning decisions had on the sustainability of the WGWSS. The purpose of Section 4.4 is to apply this understanding of the SI and to show the effect an optimal operating plan has on four interests for water in the WGWSS. The four interests for water are expressed in terms of their corresponding CI and are broadly classified into environmental (CI_{env}), social (CI_{socio}), consumptive (CI_{cons}), and system-wide interests (CI_{sys}) - refer to Equations 4.1 to 4.4 for details regarding the calculation of the four CI values. Section 4.4 does not introduce any additional O-S model runs; instead it investigates two optimal operating plans under Run (A1). Run (A1) is the higher order MOOP of the WGWSS which was described in Section 3.3 and was later used as a point of reference in the analysis of the higher order MOOPs in Section 4.3. In order to appreciate the full range of optimal operating plans that have been found, the two plans analysed correspond to those that achieve the highest and lowest SI. These operating plans are compared to the base case operating plan (BC01) in order to show the effect of different combinations of operating rules on the four interests for water.

4.4.1 Problem formulation and model setup

Whilst the higher order MOOP referred to as 'Run (A1)' has already been presented in Section 4.3.1, the problem is briefly described again for the reader's convenience and for completeness of Section 4.4. The problem for Run (A1) is to optimise the system operating rules for the WGWSS with regards to 18 competing objectives which consider environmental, social, consumptive, and system-wide interests for water - refer to Equations 4.9 to 4.26 in Section 4.3.1. As explained in Section 3.3, the problem is formulated based on the assumption that the sustainability of the WGWSS is measured in terms of three performance metrics (i.e. reliability, resiliency, and vulnerability) concerning the above four interests for water.

4.4.2 Modelling results and discussion

4.4.2.1 Objective space

As explained for Run (A1) in Section 4.3, the O-S model was run for five generations and the population with the highest ranked SI operating plan was selected for analysis. The O-S model found a total of 56 optimal operating plans forming the Pareto front. Figure 4.31 shows the corresponding SI value for each optimal plan against its normalised rank. The SI curve shows that the highest ranked SI operating plan is Plan no. 11 (shown with a green square marker) and that one of the lowest ranked SI operating plans is Plan no. 6 (shown with a red cross marker). Following the O-S modelling procedure, the dominance test was performed on the 56 optimal plans and the base case operating plan (BC01) in order to determine the status of BC01 (refer Equation 2.2 for further details regarding the possible outcomes from the dominance test). The test concluded that BC01 was not dominated by any of the 56 optimal plans under Run (A1) and was therefore an optimal operating plan. Given this outcome, BC01 is included in the SI curve as a point of reference (shown with a black open circle marker) and is not to be confused with the 56 optimal plans that were found by the O-S model under Run (A1).

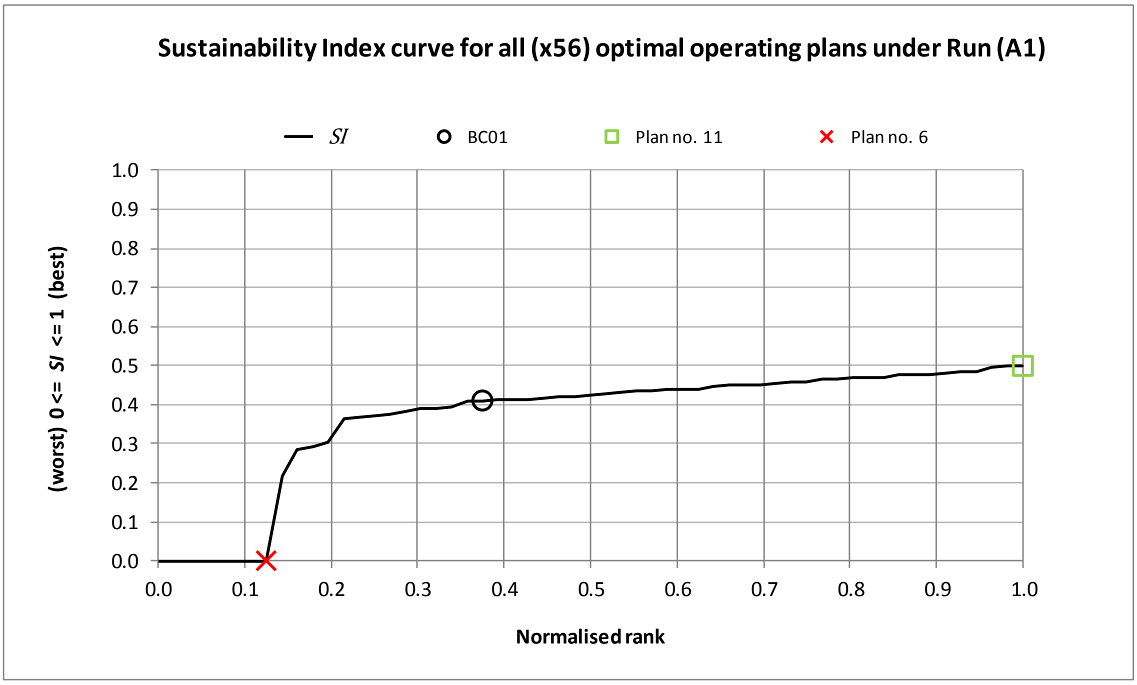


Figure 4.31 Sustainability Index curve for all (x56) optimal operating plans under Run (A1)

In terms of the level of sustainability that can be achieved in the WGWSS, Figure 4.31 shows that BC01 is neither the best nor the worst optimal operating plan. The gradient of the curve between Plan no. 11 and BC01 is relatively constant which indicates that 63% of all the optimal plans (or 35 out of 56 plans) have a similar level of diversity and that this diversity increases for the 14 plans that are ranked in the range between BC01 and Plan no. 6. Thus, choosing one optimal plan over another among the 35 plans will result in a similar level of improvement/deterioration in terms of the 18 objective functions considered. As to which of the 18 objectives have improved and which of those have deteriorated, this can be determined by analysing the results further. The seven lowest ranked SI operating plans represent a combination of planning decisions which have resulted in at least one of the component-level indices with a value of nil (i.e. CI_{env}, CI_{socio}, CI_{cons}, and/or CI_{sys}).

Figure 4.32 shows the SI curve for Run (A1) together with the corresponding CI curves representing environmental (CI_{env}), social (CI_{socio}), consumptive (CI_{cons}), and system-wide (CI_{sys}) interests for water. As explained in Section 4.2.2.1, the gradient of the SI curve represents the diversity of the operating plans with respect to the objective space. A larger gradient represents operating plans which are more diverse than those

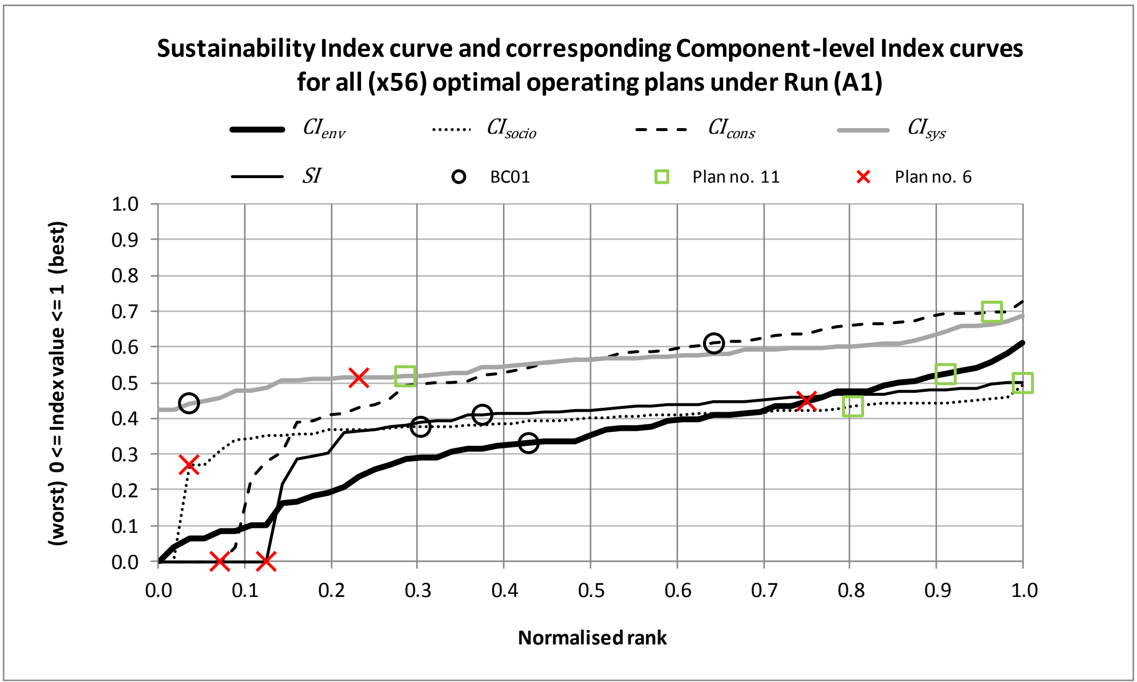


Figure 4.32 Sustainability Index curve and corresponding Component-level Index curves for optimisation-simulation modelling scenario, Run (A1)

that produce a section of curve with a smaller gradient. The same principle can be applied to the CI curve except that the diversity of operating plans relates to a single interest for water. For instance, the diversity of plans in terms of system-wide interests is relatively constant compared to the diversity of plans in terms of consumptive interests, particularly for those 40% of optimal plans between the normalised rank values of 0 and 0.4. Table 4.6 is a summary of the objective function (f) values, CI values, and SI values for BC01, Plan no. 11, and Plan no. 6.

Table 4.6 Objective function values, Component-level Index values, and Sustainability Index values for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan

Objective function (f_x), Component-level Index (CI_i), and Sustainability Index (SI)	Description	Values of f_x (%), CI_i (italic font), and SI (**bold italic font**)		
		BC01	Run (A1) - Plan no. 11	Run (A1) - Plan no. 6
$Max, f_1 = Rel_{env}$	Reliability of nil environmental flow deficits - Equation (4.9)	25%	38%	38%
$Max, f_2 = Res_{env}$	Resiliency of nil environmental flow deficits - Equation (4.10)	16%	38%	25%
$Min, f_3 = Vul_{env}$	Vulnerability of environmental flow deficits - Equation (4.11)	10%	2%	4%
CI_{env}	*Environmental Component-level Index - Equation (4.1)*	*0.33*	*0.52*	*0.45*
$Max, f_4 = Rel_{LL}$	Reliability of volume at Lake Lonsdale exceeding 5,379 ML - Equation (4.12)	61%	92%	70%
$Max, f_5 = Res_{LL}$	Resiliency of volume at Lake Lonsdale exceeding 5,379 ML - Equation (4.13)	8%	3%	8%
$Min, f_6 = Vul_{LL}$	Vulnerability of volume at Lake Lonsdale falling below 5,379 ML - Equation (4.14)	26%	13%	23%
$Max, f_7 = Rel_{LF}$	Reliability of volume at Lake Fyans exceeding 1,761 ML - Equation (4.15)	99%	100%	93%
$Max, f_8 = Res_{LF}$	Resiliency of volume at Lake Fyans exceeding 1,761 ML - Equation (4.16)	33%	100%	1%
$Min, f_9 = Vul_{LF}$	Vulnerability of volume at Lake Fyans falling below 1,761 ML - Equation (4.17)	1%	0%	6%
$Max, f_{10} = Rel_{RR}$	Reliability of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (4.18)	86%	92%	85%
$Max, f_{11} = Res_{RR}$	Resiliency of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (4.19)	2%	3%	3%
$Min, f_{12} = Vul_{RR}$	Vulnerability of volume at Rocklands Reservoir falling below 69,600 ML - Equation (4.20)	24%	17%	24%
CI_{socio}	*Social Component-level Index - Equation (4.2)*	*0.38*	*0.43*	*0.27*
$Max, f_{13} = Rel_{cons}$	Reliability of nil consumptive user deficits - Equation (4.21)	54%	69%	0%
$Max, f_{14} = Res_{cons}$	Resiliency of nil consumptive user deficits - Equation (4.22)	43%	51%	0%
$Min, f_{15} = Vul_{cons}$	Vulnerability of consumptive user deficits - Equation (4.23)	2%	3%	2%
CI_{cons}	*Consumptive Component-level Index - Equation (4.3)*	*0.61*	*0.70*	*0.00*
$Max, f_{16} = Rel_{alloc}$	Reliability of full water allocations - Equation (4.24)	94%	96%	81%
$Max, f_{17} = Res_{alloc}$	Resiliency of full water allocations - Equation (4.25)	14%	20%	26%
$Min, f_{18} = Vul_{alloc}$	Vulnerability of reduced water allocations - Equation (4.26)	36%	27%	35%
CI_{sys}	*System-wide Component-level Index - Equation (4.4)*	*0.44*	*0.52*	*0.51*
SI	*Sustainability Index - Equation (4.5)*	***0.41***	***0.50***	***0.00***

'f_x' refers to objective function x which is defined in Section 4.3.1.
'CI_i' refers to the Component-level Index for the i^{th} interest for water as defined in Section 4.1.
'SI' refers to the Sustainability Index for the Wimmera-Glenelg Water Supply System as defined in Equation 4.5.
'Max, Min' refer to the maximisation or minimisation of f_x as defined in Equations 4.9 to 4.26.
'Rel, Res, Vul' refer to the reliability, resiliency, and vulnerability performance metrics respectively, as defined in Section 3.2.4.
'env' refers to environmental interests for water as defined in Section 3.2.3.1.
'LL, LF, RR' refer to social interests for water at Lake Lonsdale, Lake Fyans, and Rocklands Reservoir respectively, as defined in Section 3.2.3.2.
'$cons$' refers to consumptive interests for water as defined in Section 3.2.3.3.
'$alloc$' refers to system-wide interests for water as defined in Section 3.2.3.4.

The results in Table 4.6 are organised in order of the objective functions and the corresponding CI, as follows:

- Objective functions, f_1 to f_3, represent the three environmental (env) interests for water expressed in terms of nil environmental flow deficits – refer to Equations 4.9 to 4.11;
- Objective functions, f_4 to f_{12}, represent the nine social ($socio$) interests for water expressed in terms of the volume held in Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR) – refer to Equations 4.12 to 4.20;
- Objective functions, f_{13} to f_{15}, represent the three consumptive ($cons$) interests for water expressed in terms of nil consumptive flow deficits – refer to Equations 4.21 to 4.23; and
- Objective functions, f_{16} to f_{18}, represent the three system-wide interests for water expressed in terms of water allocations ($alloc$) – refer to Equations 4.24 to 4.26.

The last row of Table 4.6 shows the SI values for all three optimal operating plans which are calculated from the four corresponding component-level indices (i.e. CI_{env}, CI_{socio}, CI_{cons}, and CI_{sys}).

The shaded results represent the best outcome for each objective function, either in terms of the highest values for the those objective functions that were maximised (i.e. reliability and resiliency), or the lowest values of those objective functions that were minimised (i.e. vulnerability). Similarly, the shaded results for the CI and SI values are the best outcomes in terms of the highest values. For each of the four component-level indices, Plan no. 11 clearly achieves the highest CI due it having a combination of either the highest number and/or magnitude for the corresponding objective functions. On this basis, it follows that Plan no. 11 has the highest SI value (0.5), followed by BC01 (0.41), and Plan no. 6 has the lowest SI value (0). The reason for the nil SI value for Plan no. 6 is due to at least one of the four component-level indices returning a nil CI value (refer to Equations 4.1 to 4.4 for further details regarding the calculation of the CI). Similarly, the reason for a nil CI value is due to at least one of the corresponding objective functions returning a nil f value. In this case, the results for Plan no. 6 show that the nil CI_{cons} value stems from the nil values given by f_{13} and f_{14}. The reason(s) for these objective functions returning a nil value is discussed in Section 4.4.2.3.

Table 4.6 also highlights an interesting point which may not be obvious to the DM when analysing the results in the objective space. The results show that the relativities among optimal plans in terms of SI does not always result in the same relativities in terms of CI. It is important for the DM to be aware of this as it may be assumed that an optimal plan which achieves the highest SI value is due to it having the highest CI value for all interests for water. To explain these relativities, the reader is referred to the SI value for Plan no. 11 (0.5) which is higher than that for BC01 (0.41) and which is also higher than that for Plan no. 6 (0). In this case, the same relativity amongst plans occurs in terms of the corresponding CI values for Plan no. 11 (i.e. $CI_{env} = 0.52$, $CI_{socio} =$ 0.43, $CI_{cons} = 0.7$, and $CI_{sys} = 0.52$) which are higher than their respective CI values for BC01 (i.e. $CI_{env} = 0.33$, $CI_{socio} = 0.38$, $CI_{cons} = 0.61$, and $CI_{sys} = 0.44$) and which are also higher than those for Plan no. 6 (i.e. $CI_{env} = 0.45$, $CI_{socio} = 0.27$, $CI_{cons} = 0$, and $CI_{sys} = 0.51$). However the relativity in SI for Plan no. 6 and BC01 (i.e. $0 < 0.41$) is not the same in terms of their corresponding CI_{env} value (i.e. $0.45 > 0.33$) and their corresponding CI_{sys} value (i.e. $0.51 > 0.44$).

4.4.2.2 Decision space

Table 4.7 to Table 4.12 summarise the results for the 24 decision variables (i.e. dv_1 to dv_{24}) in terms of their corresponding planning decision categories (refer to Table 4.1) for the base case operating plan (BC01) and for the two optimal plans found under Run (A1), i.e. the highest ranked SI operating plan (Plan no. 11) and the lowest ranked SI operating plan (Plan no. 6).

The results are analysed from the following two viewpoints, as follows:

- that the DM is interested in making changes to the base case operating rules in order to achieve the level of sustainability under Plan no. 11 (referred to as the 'progressive viewpoint'); and
- that the DM is interested in simply being aware of which base case operating rules would reduce the current level of sustainability with reference to Plan no. 6 (referred to as the 'conservative viewpoint').

Table 4.7 summarises the priority of supply planning decisions, dv_1 to dv_7. These priorities relate to the order in which water is sourced from different storages for supply to meet the water demand and also the order in which the different water demands are satisfied. The results show that BC01 has more planning decisions in common with Plan no. 6 than that with Plan no. 11. In terms of the number of priority of supply decisions, six out of seven of these planning decisions are in common between BC01 and Plan no. 6 (i.e. dv_1 to dv_6) compared to the two decisions between BC01 and Plan no. 11 (i.e. dv_3 and dv_6).

Table 4.7 *Priority of supply* decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan

dv_x	Decisions	BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_1	Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?	Moora Moora Reservoir is first priority	Lake Wartook is first priority	Moora Moora Reservoir is first priority
dv_2	Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?	EWD is satisfied first	Horsham is satisfied first	EWD is satisfied first
dv_3	Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?	EWD is satisfied first		
dv_4	Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?	Flows harvested into Taylors Lake first	EWD is satisfied first	Flows harvested into Taylors Lake first
dv_5	Should consumptive demands (6) to (9) be satisfied before the EWD in Glenelg River (1) or vice versa?	EWD is satisfied first	Consumptive demands are satisfied first	EWD is satisfied first
dv_6	Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir (6) or vice versa?	Provide passing flow first		
dv_7	Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?	EWD is satisfied first	Held in storage for supply to consumptive demands first	

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
'EWDs' refers to environmental water demands.
Number in brackets refers to consumptive user demand centres and environmental flow sites shown in Figure 4.1.

In terms of the progressive viewpoint, the results suggest that achieving the level of sustainability under Plan no. 11 would require changing most of the priority of supply decisions in favour of supplying the consumptive demands before the EWDs (i.e. dv_2,

dv_5, and dv_7). The exception to this is where Plan no. 11 satisfies the EWD in Burnt Creek before water is harvested into Taylors Lake (i.e. dv_4). However, the EWD in Burnt Creek is insignificant in terms of the total consumptive demand potentially supplied from Taylors Lake (i.e. 520 ML/year out of 50,600 ML/year, or 1%). In terms of the conservative viewpoint, the results show (with the exception of dv_7) that the DM should not make any change to the priority of supply planning decisions. With respect to dv_7, the results thus far do not provide a reason for holding water in storage for supply to consumptive demands via the Wimmera Mallee Pipeline in preference to the EWD in Mt William Creek at Lake Lonsdale. Note that the Wimmera Mallee Pipeline supplies water to consumptive users (19) to (30) shown in Figure 4.1.

Table 4.8 summarises the flood reserve volume planning decisions (i.e. dv_8) for the three optimal plans. Lake Wartook is operated to provide some degree of flood attenuation whilst at the same time ensuring a very good chance of filling over the winter/spring period. A large flood reserve volume may affect the supply to consumptive demands from the storage, while a small reserve volume may cause the storage to overflow more often and result in more water being lost (in an operational sense) from the system. In terms of the progressive viewpoint, the results for dv_8 suggest that achieving the level of sustainability under Plan no. 11 would require a significant increase in the flood reserve volume for Lake Wartook. Whilst this differs from the manner in which supply to Horsham is primarily sourced from Lake Wartook, this is consistent with the priority of supply planning decision that ensures Horsham is supplied first before the EWD in MacKenzie River at Dad and Dave Weir (i.e. dv_2). The implications of such a change will be discussed in Section 4.4.2.3. The conservative viewpoint is to approximately double the flood reserve volume to that under BC01.

Table 4.8 ***Flood reserve volume*** **decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan**

dv_x	Decisions	BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_8	How much flood reserve should be provided at Lake Wartook in June?	8,807 ML	26,303 ML	14,519 ML

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

Table 4.9 compares the results for the planning decisions regarding the shares of environmental allocation in the WGWSS (i.e. dv_9 to dv_{11}). The maximum annual (regulated) environmental allocation is 41,560 ML in the WGWSS. However, for modelling purposes the 1,000 ML allocation for supply to wetlands is aggregated together with GWMWater's recreation allocation of 2,590 ML and is not considered to be water for environmental purposes (refer to Section 3.2.3.4 for further details regarding water allocations in the WGWSS). The remaining 40,560 ML allocation is released for environmental purposes at four locations within the headworks, namely; the Glenelg River at Rocklands Reservoir (i.e. dv_9), MacKenzie River at Lake Wartook (i.e. dv_{10}), Mt William Creek at Lake Lonsdale (i.e. dv_{11}), and the Wimmera River at Taylors Lake.

Table 4.9 ***Share of environmental allocation*** **decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan**

dv_x	Decisions	BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_9	How much of the environmental water allocation should be released in the Glenelg River basin?	Up to 40% of the environmental water allocation	Up to 15% of the environmental water allocation	Up to 27% of the environmental water allocation
dv_{10}	How much of the environmental water allocation should be released in the Wimmera basin at Lake Wartook?	Up to 30% of the remaining share of the environmental water allocation after that provided for the Glenelg basin	Up to 2% of the remaining share of the environmental water allocation after that provided for the Glenelg basin	Up to 68% of the remaining share of the environmental water allocation after that provided for the Glenelg basin
dv_{11}	How much of the environmental water allocation should be released in the Wimmera basin at Lake Lonsdale?	Up to 60% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook	Up to 2% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook	Up to 90% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

Note that the Taylors Lake environmental allocation share is not included in Table 4.9, as it is by default the remaining share of the environmental allocation after that provided at Rocklands Reservoir, Lake Wartook, and Lake Lonsdale. Refer to Section 3.3.2.3 for further details regarding the approach used to calculate each environmental allocation share. In terms of the progressive viewpoint, the results for dv_9 suggest that achieving the level of sustainability under Plan no. 11 would require a significant change to the shares in terms of the Wimmera and Glenelg basins, where 25% out of the 40% share that was allocated to the Glenelg basin would need to be re-allocated to the Wimmera basin. Moreover, the shares within the Wimmera basin would also change significantly so that virtually all of the environmental water (96% of the Wimmera basin's share) would be available from Taylors Lake rather than shared between Lake Lonsdale (i.e. dv_{11}) and Lake Wartook (i.e. dv_{10}). Whilst this differs from the current shares of environmental allocation under BC01, this is consistent with the aforementioned planning decisions for Plan no. 11 as follows:

- the increased flood reserve volume at Lake Wartook under Plan no. 11 (i.e. dv_8) would result in greater volumes released to the MacKenzie River and Burnt Creek downstream and mean that EWDs along these stream reaches would be satisfied in transit. This would have the effect of reducing the need to reserve a share of environmental allocation at Lake Wartook as is currently the case under BC01; and
- holding water in Lake Lonsdale for supply to consumptive demands via the Wimmera Mallee Pipeline under Plan no. 11 (i.e. dv_7) together with the increased share of environmental allocation at Taylors Lake, would have the effect of reducing the need to reserve a share of environmental allocation at Lake Lonsdale. In essence, this would mean that Lake Lonsdale would no longer be needed for supplying EWDs (as is currently the case under BC01) but instead required for consumptive purposes. The implications of such changes will be discussed in Section 4.4.2.3.

In contrast to the above, the conservative viewpoint is to maintain approximate shares of environmental allocation to that under BC01.

Table 4.10 compares the results for the flow path planning decisions (i.e. dv_{12} and dv_{13}). Decision variable dv_{12} provides a flow path for resources in the eastern parts of the WGWSS to supply EWDs in the Wimmera River and consumptive demands via the Wimmera Mallee Pipeline. These resources include catchment flows intercepted by Fyans Creek and Mt William Creek and water held in Lake Bellfield, Lake Fyans and Lake Lonsdale. Decision variable dv_{13} relates to the maintenance of water quality in terms of the mixing of water sourced from Lake Bellfield with that sourced from the Wimmera River via Taylors Lake. The three possible outcomes for dv_{13} are provided in Section 3.3.2.4.

Table 4.10 *Flow path* decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan

dv_x	Decisions	BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_{12}	Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?	Harvesting of flows into Wimmera Inlet Channel is allowed		
dv_{13}	Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?	Yes, in a proportion based on the volume in Lake Bellfield	No mixing via the Bellfield-Taylors Pipeline*	Yes, according to relative storage targets and drawdown priorities for Lake Bellfield and Taylors Lake

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
* Mixing of water from Lake Bellfield and Taylors Lake can still occur provided that dv_{12} allows for harvesting of flows into Wimmera Inlet Channel.

In terms of both the progressive and conservative viewpoints, the results for dv_{12} show that Mt William Creek flows should be harvested into the Wimmera Inlet Channel. In terms of dv_{13}, the results suggest that the progressive viewpoint of achieving the level of sustainability under Plan no. 11 would require a significant change in terms of the flow path used to transfer water from Lake Bellfield to Taylors Lake. Whilst this differs from the manner in which the two storages operate, this decision is consistent with holding water in Lake Lonsdale for supply to meet consumptive demands via the Wimmera Mallee Pipeline (i.e. dv_7). In essence, this would mean that Lake Bellfield would make more water transfers to Lake Lonsdale for consumptive supply purposes rather than using the Bellfield-Taylors Pipeline (as is currently the case under BC01).

The implications of such changes will be discussed in Section 4.4.2.3. In terms of the conservative viewpoint, the results for dv_{13} suggest that the Bellfield-Taylors Pipeline be used to allow water from Lake Bellfield to be mixed (in one way or another) with water from Taylors Lake.

Table 4.11 and Table 4.12 summarise the planning decisions relating to storage maximum operating volumes (i.e. dv_{14} to dv_{20}) and storage drawdown priorities and storage targets (i.e. dv_{21} to dv_{24}) respectively. Interestingly, the similarity in results that occurs between BC01 and Plan no. 6 for planning decisions dv_1 to dv_6 and dv_8 to dv_{13} does not occur for planning decisions dv_{14} to dv_{24}; instead there is more similarity between Plan no. 11 and Plan no. 6. This change in pattern is observed in the total storage maximum operating volumes (shown in italic font in Table 4.11), the storage drawdown priorities (shown in Table 4.12), and the total storage volumes for the second and third points on the target curve (shown in italic font in Table 4.12).

Table 4.11 ***Storage maximum operating volume (MOV)*** **decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan**

dv_x	Decisions	BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_{14}	Toolondo Reservoir MOV	92,430 ML	46,215 ML	18,486 ML
dv_{15}	Lake Lonsdale MOV	Inlet is closed	Inlet is closed	Inlet is open
dv_{16}	Lake Bellfield MOV	76,000 ML	30,400 ML	22,800 ML
dv_{17}	Taylors Lake MOV	26,960 ML	30,330 ML	3,370 ML
dv_{18}	Rocklands Reservoir MOV	261,000 ML	208,800 ML	174,000 ML
dv_{19}	Lake Lonsdale MOV	53,300 ML	52,000 ML	39,000 ML
dv_{20}	Moora Moora Reservoir MOV	6,300 ML	2,520 ML	3,780 ML
Total storage maximum operating volume		*515,990 ML*	*370,265 ML*	*261,436 ML*

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

Table 4.12 ***Storage draw down priority and storage target*** **decisions for the base case operating plan (BC01) and for two optimal operating plans under Run (A1) i.e. Plan no. 11 - highest ranked SI operating plan, and Plan no. 6 - lowest ranked SI operating plan**

dv_x	Decisions		BC01	Run (A1) – Plan no. 11	Run (A1) – Plan no. 6
dv_{21}	What should be the drawdown priority of the headworks storages?	Lake Wartook	2nd	6th	1st
		Moora Moora Reservoir	1st	4th	2nd
		Horsham storages	3rd	2nd	3rd
		Rocklands Reservoir	8th	8th	8th
		Toolondo Reservoir	4th	7th	5th
		Lake Bellfield	6th	3rd	6th
		Lake Fyans	7th	5th	4th
		Taylors Lake	5th	1st	7th
dv_{22}	What should be the second point on the target curve for the headworks storages?	Lake Wartook	10,000 ML	8,790 ML	11,720 ML
		Moora Moora Reservoir	2,000 ML	5,040 ML	1,890 ML
		Horsham storages	328 ML	66 ML	197 ML
		Rocklands Reservoir	69,540 ML	174,000 ML	104,400 ML
		Toolondo Reservoir	5,000 ML	9,243 ML	64,701 ML
		Lake Bellfield	10,000 ML	23,568 ML	15,712 ML
		Lake Fyans	2,500 ML	9,230 ML	1,846 ML
		Taylors Lake	8,500 ML	5,420 ML	5,420 ML
	Total volume for second point on target curve		*107,868 ML*	*235,357 ML*	*205,886 ML*
dv_{23}	What should be the third point on the target curve for the headworks storages?	Lake Wartook	29,300 ML	27,249 ML	24,026 ML
		Moora Moora Reservoir	6,300 ML	5,922 ML	6,300 ML
		Horsham storages	328 ML	249 ML	315 ML
		Rocklands Reservoir	115,900 ML	330,600 ML	201,840 ML
		Toolondo Reservoir	46,250 ML	50,837 ML	73,020 ML
		Lake Bellfield	20,000 ML	51,064 ML	72,275 ML
		Lake Fyans	10,000 ML	16,614 ML	8,492 ML
		Taylors Lake	8,500 ML	11,924 ML	24,932 ML
	Total volume for third point on target curve		*236,578 ML*	*494,459 ML*	*411,199 ML*
dv_{24}	What should be the fourth point on the target curve for the headworks storages?	Lake Wartook	29,300 ML	28,685 ML	27,718 ML
		Moora Moora Reservoir	6,300 ML	6,187 ML	6,300 ML
		Horsham storages	328 ML	257 ML	328 ML
		Rocklands Reservoir	260,775 ML	334,080 ML	245,688 ML
		Toolondo Reservoir	46,250 ML	84,111 ML	84,666 ML
		Lake Bellfield	78,560 ML	75,810 ML	73,532 ML
		Lake Fyans	10,000 ML	18,091 ML	14,473 ML
		Taylors Lake	8,500 ML	25,582 ML	25,149 ML
	Total volume for fourth point on target curve		*440,013 ML*	*572,803 ML*	*477,853 ML*

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

In terms of the progressive viewpoint, the results shown in Table 4.11 and Table 4.12 suggest that achieving the level of sustainability under Plan no. 11 would require a significant decrease in the total storage maximum operating volume and a significant increase in storage target volume. Whilst the results for the storage drawdown priorities cannot be structured in the same way as the storage maximum operating volumes and storage targets, the results show that the priorities under Plan no. 11 would need to change for some storages (e.g. Taylors Lake has a priority of 5th storage to be drawn down under BC01 compared to a higher priority of 1st storage under Plan no. 11). Importantly, there is consistency between these planning decisions (i.e. storage maximum operating volumes, storage drawdown priorities, and storage targets) and other relevant planning decisions under Plan no. 11. For example in the case of Rocklands Reservoir, the results for the storage drawdown priority (i.e. dv_{21}) and the total volumes for the second, third, and fourth points on the target curve (i.e. dv_{22} to dv_{24}) are consistent with planning decisions dv_5 and dv_9 as follows:

- the decrease in the storage maximum operating volume at Rocklands Reservoir from 261,000 ML under BC01 to 208,800 ML under Plan no. 11 has the effect of forcing water out of the storage and so satisfying the downstream EWD at the risk of not satisfying the consumptive demands (refer to consumptive users (6) to (9) in Figure 4.1). This planning decision is consistent with placing higher priority in supplying consumptive demands from Rocklands Reservoir over the EWD in the Glenelg River under Plan no. 11 (i.e. dv_5); and
- the increase in storage targets at Rocklands Reservoir for the second point (i.e. from 69,540 ML under BC01 to 174,000 ML under Plan no. 11, dv_{22}), for the third point (i.e. from 115,900 ML under BC01 to 330,600 ML under Plan no. 11, dv_{23}), and the fourth point (i.e. from 260,775 ML under BC01 to 334,080 ML under Plan no. 11, dv_{24}) has the effect of increasing the rate of harvest at Rocklands Reservoir. Such planning decisions are required in order to satisfy the EWD in the Glenelg River by compensating for the reduced share of environmental allocation mentioned earlier under Plan no. 11 (i.e. dv_9).

In contrast to the above, the conservative viewpoint is to maintain a relatively high level of storage maximum operating volume and a relatively low level of storage target volume.

In summary, the results for the 24 decision variables (i.e. dv_1 to dv_{24}) show that 21 out of 24 planning decisions would need to be changed from a progressive viewpoint. The three planning decisions which remain unchanged would be the two priority of supply decisions (i.e. dv_3 and dv_6) and one flow path decision (i.e. dv_{12}).

4.4.2.3 Discussion

The analysis of the three optimal operating plans (i.e. BC01, Plan no. 11, and Plan no. 6) with respect to the objective space (Section 4.4.2.1) and decision space (Section 4.4.2.2) raised the following points for further discussion:

- It was not clear from the analysis conducted as to the reason(s) for certain objective functions returning a nil value. For example in the case of Plan no. 6, it was clear from the nil values for f_{13} and f_{14} that the consumptive interests for water were significantly impacted by the operating rules under this plan, in terms of both the reliability and resiliency of nil consumptive user deficits. It was also clear that the severity of the impact borne by the consumptive interests for water under Plan no. 6 was low given by the low vulnerability value (i.e. $Vul_{cons} = 2\%$). However, the results presented were not able to provide an explanation for the source of the problem (e.g. lack of water, insufficient channel capacity, poor combination of operating rules etc) and as to whether the occurrence was system-wide or localised to one or a few areas of the WGWSS. Chapter 5 will demonstrate the importance of simulating the behaviour of the WGWSS (using simulation modelling) in order to provide such explanations.
- The changes associated with the significant increase in the flood reserve volume (i.e. dv_8) and the significant decrease in the share of environmental allocation at Lake Wartook (i.e. dv_{10}) under Plan no. 11 would require careful consideration of the social impacts in terms of the quality of water supplied to Horsham. Barton et al. (2011) explained that one of the difficult water management issues during the Millennium Drought was the number of complaints with regards to the colour and turbidity of emergency groundwater supplies which were required to augment the low levels at Lake Wartook. Whilst water quality is not explicitly accounted for in the simulation model, a new objective function similar to those which account for the social interests for

water (i.e. f_4 to f_{12}), could be used in the formulation of the higher order MOOP as a proxy for water quality considerations at Lake Wartook.

- The changes associated with the operation of Lake Bellfield and Lake Lonsdale (including the use of the Bellfield-Taylors Pipeline) would require careful consideration of the consumptive user and social impacts. Based on the contractual obligation on GWMWater to supply high quality water to its customers via the Wimmera Mallee Pipeline, the consumptive user impacts would need to be assessed in terms of the relatively lower water quality sourced from Lake Lonsdale (GWMWater 2011). Given the community effort that was involved in advocating for the construction of the Bellfield-Taylors Pipeline, the social impacts would manifest themselves in terms of political backlash over the waste of public funds and essentially the decommissioning of the pipeline under Plan no. 11. Political backlash is also anticipated with the changed role of Lake Lonsdale from primarily providing environmental flows under BC01 to one of primarily supplying consumptive users. This contentious issue was explained in detail under Section 3.2.3.1. Moreover, given that Lake Lonsdale is the most inefficient storage of the headworks, there is a need to consider its operation in terms of the evaporative loss that occurs off its surface. Chapter 5 will investigate the efficiency of the system as part of investigations into the optimal operating plans for the WGWSS assuming future greenhouse gas emissions.

In essence, the above points highlight a need to ascertain the level of risk associated with the implementation of Plan no. 11 or Plan no. 6. Given the absence of a risk-benefit analysis, it is not clear from the results in Sections 4.4.2.1 and 4.4.2.2 as to the benefit of implementing one optimal plan over another in terms of the improvement in SI versus the associated risk in potentially introducing untested operating rules. This highlights the importance of using simulation modelling in order to emulate the behaviour of the system under the effect of such unproven optimal operating plans. This simulation modelling output would provide the DM with a more detailed appreciation of the impacts (beyond that provided by the performance metrics alone) without any risk to human life, ecological health, and the water resources of the WGWSS.

4.4.3 Conclusions

Section 4.4 presented a higher order MOOP for the purposes of showing the effect an optimal operating plan has on four interests for water in the WGWSS. The outcomes of this analysis are summarised below:

- In Section 4.2 it was shown that the gradient of the SI curve represents the diversity of the operating plans with respect to the objective space. A larger gradient represents operating plans which are more diverse than those that produce a section of curve with a smaller gradient. The same principle was applied to the CI curve in Section 4.4 except that the diversity of operating plans related to a single interest for water. It was shown that for optimal plans under Run (A1), the diversity of plans in terms of system-wide interests was relatively constant compared to the diversity of plans in terms of consumptive interests, particularly for those 40% of optimal plans between the normalised rank values of 0 and 0.4.
- The relativities among optimal plans in terms of SI does not always result in the same relativities in terms of CI. It was shown that the highest ranked SI optimal operating plan (i.e. Plan no. 11) consistently achieved higher CI values, for all four interests for water, compared to BC01 and one of the lowest ranked SI optimal operating plan (i.e. Plan no. 6). However, for Plan no. 6 which had a lower SI value than that for BC01, the CI values for Plan no. 6 in terms of the environmental interests (i.e. CI_{env}) and system-wide interests (i.e. CI_{sys}) were actually higher than the corresponding values for BC01. This is important as it may be assumed that an optimal plan which achieves the highest SI value also has the highest CI value for all interests for water, which may not always be the case.
- The results for the 24 decision variables (i.e. dv_1 to dv_{24}) showed that 21 out of 24 planning decisions would need to be changed in order for the base case operating plan to achieve the level of sustainability under Plan no. 11. The three planning decisions which remain unchanged would be the two priority of supply decisions (i.e. dv_3 and dv_6) and one flow path decision (i.e. dv_{12}).

Whilst the analysis of the O-S modelling results showed the effect of the three optimal operating plans on the four interests for water, it was not possible to ascertain the level of risk associated with the implementation of Plan no. 11 or Plan no. 6. On relative terms, it was expected that making changes to most of the base case operating rules would inherently have a higher level of risk and unpleasantness compared to that which makes little or no changes to the status quo (e.g. 21 out of 24 planning decisions as mentioned above). It is worth mentioning that the consequences of failure in water resources management are often significant in monetary terms and may expose people to dangerous circumstances and harm the health of ecosystems. This highlights the importance of using simulation modelling in order to emulate the behaviour of the system and better understand the effects of (potentially) untested optimal operating plans on all interests for water. This simulation modelling output provides the DM with a more detailed appreciation of the impacts (beyond that provided by the performance metrics alone) without any risk to human life, ecological health, and the water resources of the system. Moreover, it would be prudent to test the optimality of any preferred optimal operating plans under a range of hydro-climatic conditions so as to ensure that these plans are sufficiently robust to withstand future changes in climate. Both these important areas of consideration (i.e. simulation modelling and climate change) are the focus of the O-S modelling investigations in Chapter 5.

4.5 Summary

Chapter 4 presented various MOOPs with the aim of demonstrating the effectiveness of the SI in terms of analysing optimal operating plans along the Pareto front. Specifically, it presented an approach for (i) ranking alternatives; (ii) assessing the level of influence that a set of operating rules has on a system's sustainability; and (iii) showing the effect of alternative operating plans on various interests for water.

Section 4.2 presented a lower order MOOP for the purposes of demonstrating the effectiveness of the SI in terms of ranking optimal operating plans. The problem was formulated accounting for three environmental objectives expressed in terms of environmental flow deficits. This MOOP was solved for seven planning decisions that represented the storage maximum operating volumes of six headworks storages within the WGWSS (i.e. dv_{14} to dv_{20}). The analysis of the O-S modelling results showed that there were six combinations of maximum operating volumes which constituted the Pareto front with varying levels of sustainability (i.e. $0.11 < SI < 0.47$). This study of the lower order MOOP showed that the SI was a useful tool for evaluating and comparing optimal operating plans with respect to the objective space and decision space. In terms of the objective space, ranking and plotting the SI against its normalised rank provided a visual representation of the Pareto front. The results showed that the gradient of the SI curve represented the diversity of the operating plans with respect to the objective space. A larger gradient represented operating plans which were more diverse than those that produced a section of curve with a smaller gradient. In terms of the decision space, the corresponding decision variable values were plotted together with the SI curve in order to inform the DM about how different planning decisions influenced a system's sustainability. The importance of problem formulation and the need to take explicit account for all interests for water was also discussed given that the results had shown that some optimal plans did not consider non-environmental interests for water.

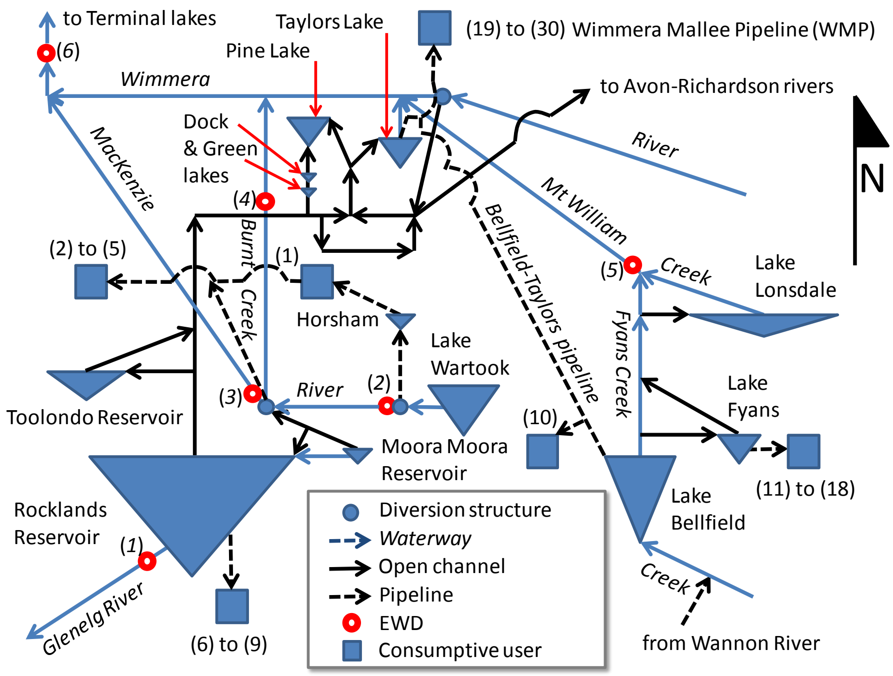
Section 4.3 presented a series of higher order MOOPs for the purposes of assessing the level of influence that a set of operating rules had on the sustainability of the WGWSS. The problem was formulated accounting for 18 competing objectives which considered environmental, social, consumptive, and system-wide interests for water. The assessment was based on the results of six O-S modelling runs which were used to solve for one planning decision category at a time. The six categories of planning decisions represented *priorities of supply* between different sources of supply and between different user groups (Run B1); a *storage flood reserve volume* which provided flood attenuation (Run C1); *shares of environmental allocation* for apportioning environmental water allocations between river basins (Run D1); the preference of alternative *flow paths* for the harvesting and/or transfer of water (Run E1); *storage maximum operating volumes* for six harvesting storages (Run F1); and *storage draw down priorities and storage targets* (Run G1). The six O-S modelling runs were compared to Run (A1) which was solved for all planning decision categories, representing the highest levels of sustainability (in terms of SI). One important outcome from the study was that the SI curve was a convenient and simple means to summarise the sustainability of many optimal operating plans. The results of the assessment in terms of the objective space, showed that the optimal operating plans found under Run (F1) provided the greatest diversity amongst plans along the Pareto front, particularly for those 25% of optimal plans between the normalised rank values of 0.15 and 0.4. An important observation was also made which was later confirmed as part of the decision space analysis; that the close alignment of the SI curve for Run (F1) to that for Run (A1) was evidence that the storage maximum operating volumes were indeed the most influential of all the planning decision categories considered.

Section 4.4 also presented Run (A1) but this time for the purposes of showing the effect an optimal operating plan had on four interests for water in the WGWSS. The four interests for water were broadly classified into environmental (CI_{env}), social (CI_{socio}), consumptive (CI_{cons}), and system-wide interests (CI_{sys}) expressed in terms of their corresponding CI. The outcomes of Section 4.2, in terms of the ranking of optimal operating plans using the SI, were applied to the CI with regards to a particular interest for water. It was shown that for optimal plans under Run (A1), the diversity of plans in terms of system-wide interests (i.e. CI_{sys}) was relatively constant compared to the diversity of plans in terms of consumptive interests (i.e. CI_{cons}), particularly for those 40% of optimal plans between the normalised rank values of 0 and 0.4. One important observation was that the relativities among optimal plans in terms of SI did not always result in the same relativities in terms of CI. It was shown that the highest ranked SI optimal operating plan (i.e. Plan no. 11) consistently achieved higher CI values, for all four interests for water, compared to BC01 and the lowest ranked SI optimal operating plan (i.e. Plan no. 6). However, for Plan no. 6 which had a lower SI value than that for BC01, the CI values for Plan no. 6 in terms of the environmental interests (i.e. CI_{env}) and system-wide interests (i.e. CI_{sys}) were actually higher than the corresponding values for BC01. It was explained that this was important information for the DM as it may be assumed that an optimal plan which achieves the highest SI value also has the highest CI value for all interests for water, which may not always be the case. Another important finding of the study was that 21 out of 24 planning decisions would need to be changed in order to attain the highest level of sustainability for the WGWSS. It was shown that the three planning decisions which remain unchanged would be the two priority of supply decisions (i.e. dv_3 and dv_6) and one flow path decision (i.e. dv_{12}). The need for a risk-benefit analysis of the optimal operating plans was discussed and simulation modelling was offered as a means to develop a better understanding of the effects of (potentially) untested operating plans on all interests for water.

Chapter 5. Selection of preferred optimal operating plans under various future hydro-climatic scenarios

5.1 Introduction

This chapter applies the analytical approach presented and applied in Chapter 4 to multi-objective optimisation problems (MOOPs) considering two plausible future greenhouse gas (GHG) emission scenarios. The aims of Chapter 5 are to (i) evaluate and compare the optimal operating plans under historic hydro-climatic conditions against the optimal operating plans under these GHG emission scenarios; and (ii) select the most preferred optimal operating plan(s) by taking into account stakeholders' preferences. For this purpose, two MOOPs are formulated for the Wimmera-Glenelg Water Supply System (refer Figure 5.1) and solved using the optimisation-simulation (O-S) modelling approach described in Chapter 3. Note that Figure 5.1 is the same as Figure 4.1 and Figure 3.2.



Note: Numbers in brackets refer to environmental water demands or EWDs (italic font) and consumptive water demands (regular font) configured in the Wimmera-Glenelg REALM model (refer to Section 3.2.2).

Figure 5.1 Schematic of the Wimmera-Glenelg Water Supply System (not to scale)

As explained in Section 4.1, Chapter 1 described important factors related to solving higher order MOOPs which influenced the research methodology, viz; the slow convergence of solutions to the Pareto front; and the high computational costs required to progress this search. An increase in objectives has the effect of slowing the progression (i.e. *convergence*) of the population of solutions to the Pareto front. This slow convergence is largely attributed to the dominance test which is applied to the solutions of the population; resulting in a greater number of O-S modelling generations to progress the solutions towards the Pareto front. The term *generation* refers to a (single) iteration of the O-S model. An increase in the number of generations requires greater computational processing effort, which may be addressed through parallel computing processes. However, such parallel computing capabilities were not available for this thesis, which meant that simulation runs for all solutions of the population had to be completed in series (i.e. one run at a time) before the optimisation search could be executed. For these reasons (of slow convergence and high computational costs), the number of generations performed by the O-S model was limited to five in number (throughout this thesis). Importantly, this is not to be mistaken as a research limitation given that the novelty of this study is that of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*.

As explained in Section 4.1, Chapter 3 described an approach for the formulation of MOOPs and applied it to a higher order MOOP for the WGWSS. A higher order MOOP is defined in this thesis as a problem that is formulated with more than three objective functions. All the major interests for water were explicitly taken into account and were used as the basis for 18 objective functions which directed the search towards the set of optimal operating plans which were collectively referred to as the *Pareto front*. The decision variables were expressed in terms of 24 water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. For the reader's convenience and for completeness of Chapter 5, these planning decisions are provided again in Table 5.1.

Chapter 3 also presented the Sustainability Index (SI) as a means to measure the sustainability of the WGWSS based on the performance of four components. Again for the reader's convenience and for completeness of Chapter 5, these component-level indices are used for the evaluation and comparison of optimal operating plans within Chapter 5 (refer to Equations 5.1 to 5.4).

Table 5.1 Water management planning decisions for the WGWSS

Category	dv_x	Decisions	Value range
Priority of supply	dv_1	Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?	Either Lake Wartook or Moora Moora Reservoir is first priority and the other is a supplementary source of supply
	dv_2	Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?	Either Horsham (1) or EWD (2) is satisfied first
	dv_3	Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?	Either harvest flows into Taylors Lake or EWD (3) is satisfied first
	dv_4	Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?	Either harvest flows into Taylors Lake or EWD (4) is satisfied first
	dv_5	Should consumptive demands (6) to (9) be satisfied before the EWDs in Glenelg River (1) or vice versa?	Either consumptive demands (6) to (9) or EWD (1) is satisfied first
	dv_6	Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir or vice versa?	Either harvest flows into WIC or provide passing flow (6) first
	dv_7	Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?	Either hold water in Lake Lonsdale for consumptive demands (19) to (30) or supply EWD (5) first
Flood reserve volume	dv_8	How much flood reserve should be provided at Lake Wartook in June?	Either hold no reserve or hold a maximum of up to the full storage capacity in June
Share of environ-mental allocation	dv_9	How much of the environmental water allocation should be released in the Glenelg River basin?	Either no share or up to 100% of the environmental water allocation
	dv_{10}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Wartook?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin
	dv_{11}	How much of the environmental water allocation should be released in the Wimmera River basin at Lake Lonsdale?	Either no share or up to the remaining share of the environmental water allocation after that provided for the Glenelg River basin and that at Lake Wartook
Flow path	dv_{12}	Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?	Either harvest flows into Wimmera Inlet Channel or pass all flows to Wimmera River
	dv_{13}	Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?	Supply from Lake Bellfield may result in one of three outcomes; nil, a proportion based on the volume in storage, or 100%
Storage maximum operating volume	dv_{14}	Toolondo Reservoir	0 to 92,430 ML
	dv_{15}	Lake Lonsdale	Inlet is either open or closed
	dv_{16}	Lake Bellfield	0 to 76,000 ML
	dv_{17}	Taylors Lake	0 to 33,700 ML
	dv_{18}	Rocklands Reservoir	0 to 348,000 ML
	dv_{19}	Lake Lonsdale	0 to 65,000 ML
	dv_{20}	Moora Moora Reservoir	0 to 6,300 ML
Storage draw down priority and storage target	dv_{21}	What should be the drawdown priority of the headworks storages?	Each storage is assigned a unique draw down priority from 1 to 8
	dv_{22}	What should be the second point on the target curve for the headworks storages?	Any volume between dead storage and FSL
	dv_{23}	What should be the third point on the target curve for the headworks storages?	Any volume between the second target point and FSL
	dv_{24}	What should be the fourth point on the target curve for the headworks storages?	Any volume between the third target point and FSL

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
'EWDs' refers to environmental water demands.
Number in brackets refers to consumptive user demand centres and environmental flow sites shown in Figure 5.1.

The Component-level Index (CI_i) assumes that the sustainability for the i^{th} interest for water is measured in terms of reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i). These interests for water identified in Chapter 3 are broadly classified into environmental (env); social interests such as for recreation at Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR); consumptive interests ($cons$); and all these interests collectively in terms of system water allocations ($alloc$). Equation 5.5 is the mathematical expression for the SI. The reader is referred to Section 3.5.1 for further details regarding the basis of these equations.

$$CI_{env} = [Rel_{env} \times Res_{env} \times (1 - Vul_{env})]^{1/3} \quad (5.1)$$

$$CI_{socio} = [Rel_{LL} \times Res_{LL} \times (1 - Vul_{LL}) \times Rel_{LF} \times Res_{LF} \times (1 - Vul_{LF}) \times Rel_{RR} \times Res_{RR} \times (1 - Vul_{RR})]^{1/9} \quad (5.2)$$

$$CI_{cons} = [Rel_{cons} \times Res_{cons} \times (1 - Vul_{cons})]^{1/3} \quad (5.3)$$

$$CI_{sys} = [Rel_{alloc} \times Res_{alloc} \times (1 - Vul_{alloc})]^{1/3} \quad (5.4)$$

$$SI = \left[(CI_{env})^3 \times (CI_{socio})^9 \times (CI_{cons})^3 \times (CI_{sys})^3\right]^{1/18} \quad (5.5)$$

Chapter 3 furthermore presented a weighted sustainability index for the purposes of selecting preferred optimal operating plans from the Pareto front. It was explained that the SI could incorporate stakeholders' preferences by combining it with a set of weights to produce a weighted geometric average of the 18 performance metric values of the MOOP. Thus, the j^{th} stakeholder's Weighted Component-level Index (CI_i^j) and Weighted Sustainability Index (SI^j) are expressed as follows:

$$CI_{env}^j = \left[(Rel_{env})^{w_1^j} \times (Res_{env})^{w_2^j} \times (1 - Vul_{env})^{w_3^j}\right]^{1/(\sum_{m=1}^{3} w_m^j)} \quad (5.6)$$

$$CI_{socio}^j = [(Rel_{LL})^{w_4^j} \times (Res_{LL})^{w_5^j} \times (1 - Vul_{LL})^{w_6^j} \times (Rel_{LF})^{w_7^j} \times (Res_{LF})^{w_8^j} \times (1 - Vul_{LF})^{w_9^j} \times (Rel_{RR})^{w_{10}^j} \times (Res_{RR})^{w_{11}^j} \times (1 - Vul_{RR})^{w_{12}^j}]^{1/(\sum_{m=4}^{12} w_m^j)} \quad (5.7)$$

$$CI_{cons}^j = \left[(Rel_{cons})^{w_{13}^j} \times (Res_{cons})^{w_{14}^j} \times (1 - Vul_{cons})^{w_{15}^j}\right]^{1/(\sum_{m=13}^{15} w_m^j)} \quad (5.8)$$

$$CI_{sys}^j = \left[(Rel_{alloc})^{w_{16}^j} \times (Res_{alloc})^{w_{17}^j} \times (1 - Vul_{alloc})^{w_{18}^j}\right]^{1/(\sum_{m=16}^{18} w_m^j)} \quad (5.9)$$

$$SI^j = \left[(CI_{env}^j)^{1/(\sum_{m=1}^{3} w_m^j)} \times (CI_{socio}^j)^{1/(\sum_{m=4}^{12} w_m^j)} \times (CI_{cons}^j)^{1/(\sum_{m=13}^{15} w_m^j)} \times (CI_{sys}^j)^{1/(\sum_{m=16}^{18} w_m^j)}\right]^{1/(\sum_{m=1}^{18} w_m^j)} \quad (5.10)$$

Where,

w_m^j, refers to the j^{th} stakeholder's weights for the m^{th} performance metric

Note that the weighted geometric average with equal weights is the same as the geometric average (i.e. $SI^j = SI$ and $CI_i^j = CI_i$).

Chapter 4 formulated various MOOPs for the purposes of demonstrating the effectiveness of the SI in terms of analysing optimal operating plans along the Pareto front (assuming historical hydro-climatic conditions). One of these O-S modelling runs (referred to as "Run (A1)") was used to solve for all six planning decision categories in a single O-S model run and was used to represent the highest levels of sustainability for the WGWSS (in terms of SI). The optimal operating plans found under Run (A1) were compared to a base case scenario (referred to as the "base case operating plan") which represents the operating plan that is in place for the WGWSS at the time of writing of this thesis – refer to Section 3.2.2 for further details. Several important outcomes were established as part of this work and are summarised as follows for the reader's convenience and for completeness of Chapter 5:

a) *Ranking optimal operating plans in terms of the sustainability of the WGWSS -*
The SI, when expressed in terms of its normalised rank (referred to as "SI curve"), provides a simple visualisation of the Pareto front for all interests for water. The gradient of the SI curve represents the diversity of the operating plans with respect to the objective space (for all interests for water combined). A larger gradient represents operating plans which are more diverse than those that produce a section of curve with a smaller gradient.

b) *Assessing the level of influence that a set of operating rules has on the sustainability of the WGWSS -*
The SI curve is a convenient and simple means to summarise the sustainability (in terms of SI) of many optimal operating plans. An assessment of the SI curves for each of the six planning decision categories in Table 5.1 revealed that the planning decisions regarding the storage maximum operating volumes were the most influential of all the planning decision categories for the WGWSS.

c) *Showing the effect of alternative operating plans on various interests for water in the WGWSS -*
Similar to the outcomes for the SI above, the CI, when expressed in terms of its normalised rank (referred to as "CI curve"), provides a simple visualisation of the Pareto front in terms of a particular interest for water. The gradient of the CI curve represents the diversity of the operating plans with respect to the objective space (for that interest for water). A larger gradient represents

operating plans which are more diverse than those that produce a section of curve with a smaller gradient.

d) *The need to confirm the validity of optimal operating plans under a range of hydro-climatic conditions -*
Given the uncertainty in the impact of changes to the base case operating plan, it is important that any optimal operating plans preferred/selected by the DM be tested under a range of hydro-climatic conditions so as to ensure that these plans are sufficiently robust to withstand future changes in climate.

For the purposes of confirming the validity of the optimal operating plans found under historic hydro-climatic conditions (i.e. Run (A1)), two O-S modelling runs are undertaken, each of which assume a different but plausible GHG emission level into the future. The two GHG emission scenarios selected represent the lower and higher ends of the estimated range of GHG emissions as given by the Intergovernmental Panel on Climate Change or IPCC (IPCC, 2000). The motivation for choosing these bookend estimates is that the testing of optimal operating plans (as explained in Section 5.1d) would include the widest plausible range of future hydro-climatic conditions. The “low to medium level” and “medium to high level” GHG emission scenarios selected are estimated to result in total cumulative global carbon dioxide emissions ranging from approximately 800 GtC to 1,400 GtC and 1,400 GtC to 2,000 GtC by 2100 respectively (IPCC, 2000). The units GtC means gigatonnes of carbon. Refer to Section 3.4.2.2 for further details regarding the climate and streamflow data used in the O-S model. The low to medium level and medium to high level GHG emission scenarios are also referred to as “Run (A2)” and “Run (A3)” respectively. The O-S modelling results for Run (A1), Run (A2), and Run (A3) are analysed in terms of the objective space and decision space using the analytical approach presented in Chapter 4 i.e. using the SI and CI. The highest ranked SI operating plan found under historic hydro-climatic conditions, Run (A1), is compared to those found under the two GHG emission scenarios and the effects of future climate on the sustainability of these optimal operating plans are discussed. As a point of reference, the analysis of the modelling results also examines the effect of the two GHG emission scenarios on the base case operating plan. Refer to Section 5.2 for details of this part of the study.

Having better understood the impact of future climate on the sustainability of the WGWSS, the reader’s attention is turned to the use of the SI in the decision-making process. The process of selecting the most preferred optimal operating plan(s) from the Pareto front brings together two aspects of multi-objective optimisation, namely; (i) the quantitative information regarding the characteristics of the optimal operating plans along the Pareto front; and (ii) the higher level qualitative information in the form of stakeholders' preferences. For this purpose, three broad categories of preferences are described in terms of three DMs, namely; those that have (i) strong environmental preferences relating to ecological health of waterways including the flora and fauna that depend on these natural ecosystems; (ii) strong social preferences concerning water for recreation and for maintenance of water quality; and (iii) strong preferences for the needs of consumptive users such as for urban centres and irrigators. These stakeholder preferences are applied to the SI^j in Equation 5.10 as part of the selection process. The results of the selection process are discussed and simulation modelling is used to explain any potential knowledge gaps that may exist in the O-S modelling results. Refer to Section 5.3 for details of this part of the study.

Table 5.2 summarises the key specifications of the O-S modelling scenarios referred to in this chapter.

Table 5.2 Key specifications for O-S modelling runs referred to in Chapter 5

Scenario	Planning period	Hydro-climatic data	Reference for further information
Run (A1)	Jan 1891 to Jun 2009	Historical	Section 4.4
Run (A2)	Jan 2000 to Dec 2099	Low-medium level total cumulative global carbon dioxide emission	Section 5.2.1.1
Run (A3)		Medium-high level total cumulative global carbon dioxide emission	Section 5.2.1.2

It is important to highlight the following:

- The base case operating plan is not included in Table 5.2 as it is a simulation-only run. This operating plan is run under historic hydro-climatic conditions and the two GHG emission scenarios for the purposes of providing a point of reference in the analysis of the optimal operating plans found under the O-S modelling runs (i.e. Run (A1), Run (A2), and Run (A3)). Note that the same planning periods for the O-S modelling scenarios are used in the simulation runs for the base case operating plan.

- The water demand setup, both environmental and consumptive, are the same under all O-S modelling runs and are explained in detail in Section 3.4.1.2.2.

5.2 A MOOP for the Wimmera-Glenelg Water Supply System under two plausible future GHG emissions scenarios

For the purposes of evaluating and comparing optimal operating plans under historic hydro-climatic conditions against the optimal operating plans under future GHG emissions, two GHG emission scenarios are selected for inclusion in the O-S modelling procedure. As stated earlier, the low to medium level and medium to high level GHG emission scenarios selected are estimated to result in total cumulative global carbon dioxide emissions ranging from approximately 800 GtC to 1,400 GtC and 1,400 GtC to 2,000 GtC by 2100 respectively (IPCC, 2000). Refer to Section 3.4.1.2.1 for further details regarding the climate and streamflow data used in the O-S model. The O-S modelling results for the historic hydro-climatic conditions (Run (A1)), the low to medium level GHG emission scenario (Run (A2)), and the medium to high level GHG emission scenario (Run (A3)) are analysed in terms of the objective space and decision space using the SI and CI. For reasons of brevity, the testing of the optimal operating plans found under historic hydro-climatic conditions against those found under the two GHG emission scenarios, focuses on the highest ranked SI operating plans and compares these results to those representing the base case operating plan under the corresponding hydro-climatic conditions.

5.2.1 Problem formulation and model setup

5.2.1.1 Run (A2) – The low to medium level GHG emission scenario

Run (A2) is the same as Run (A1) except that the climate and streamflow data used in Run (A2) correspond to the low to medium level GHG emissions, whereas Run (A1) used historic hydro-climatic conditions. Note that there is a 12% reduction in the long term average annual availability of water under the low to medium GHG emission scenario compared to the historic hydro-climatic conditions. Refer to Section 5.2.2.3 for further details regarding the hydrological conditions under the low to medium GHG emission scenario. Whilst Run (A1) has already been presented in Section 4.4.1, the problem is described again for the reader's convenience and for completeness of Section 5.2. The problem is to optimise the system operating rules with regards to 18 competing objectives which consider environmental, social, consumptive, and system-wide interests for water - refer to Equations 5.11 to 5.28. It is assumed that the sustainability of the WGWSS is measured in terms of reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i) for the i^{th} interest for water. Equations 5.11 to 5.13 relate to three environmental (env) interests for water expressed in terms of nil environmental flow deficits. Equations 5.14 to 5.22 relate to nine social ($socio$) interests for water expressed in terms of the volume of the j^{th} storage (S_j) being Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR). Equations 5.23 to 5.25 relate to three consumptive ($cons$) interests for water expressed in terms of nil supply deficits. Equations 5.26 to 5.28 relate to three system-wide interests for water expressed in terms of water allocations ($alloc$).

$$\text{Maximise}, f_1 = Rel_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0}{n}\text{, where } n = 118 \text{ years} \quad (5.11)$$

$$\text{Maximise}, f_2 = Res_{env} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{env,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occured}} \quad (5.12)$$

$$\text{Minimise}, f_3 = Vul_{env} = \frac{(\sum_{t=1}^{12} Def_{env,t})/\text{No. of years } (\sum_{t=1}^{12} Def_{env,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{env,t})} \quad (5.13)$$

$$\text{Maximise}, f_4 = Rel_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML}}{n}\text{, where } n = 1{,}416 \text{ months} \quad (5.14)$$

$$\text{Maximise}, f_5 = Res_{LL} = \frac{\text{No. of months } S_{LL,t} > 5{,}379 \text{ ML follows } S_{LL,t} \leq 5{,}379 \text{ ML}}{\text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occured}} \quad (5.15)$$

$$\text{Minimise}, f_6 = Vul_{LL} = \frac{(\sum[\max\{0,(5{,}379 \text{ ML} - S_{LL,t})\}]/\text{No. of months } S_{LL,t} \leq 5{,}379 \text{ ML occurred}}{\text{Average of } S_{LL,t}} \quad (5.16)$$

$$\text{Maximise}, f_7 = Rel_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML}}{n}\text{, where } n = 1{,}416 \text{ months} \quad (5.17)$$

$$\text{Maximise}, f_8 = Res_{LF} = \frac{\text{No. of months } S_{LF,t} > 1{,}761 \text{ ML follows } S_{LF,t} \leq 1{,}761 \text{ ML}}{\text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occured}} \quad (5.18)$$

$$\text{Minimise}, f_9 = Vul_{LF} \quad \frac{(\sum[\max\{0,(1{,}761 \text{ ML} - S_{LF,t})\}]/\text{No. of months } S_{LF,t} \leq 1{,}761 \text{ ML occurred}}{\text{Average of } S_{LF,t}} \quad (5.19)$$

$$\text{Maximise}, f_{10} = Rel_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML}}{n}\text{, where } n = 1{,}416 \text{ months} \quad (5.20)$$

$$\text{Maximise}, f_{11} = Res_{RR} = \frac{\text{No. of months } S_{RR,t} > 69{,}600 \text{ ML follows } S_{RR,t} \leq 69{,}600 \text{ ML}}{\text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occured}} \quad (5.21)$$

$$\text{Minimise}, f_{12} = Vul_{RR} = \frac{(\sum[\max\{0,(69{,}600 \text{ ML} - S_{RR,t})\}]/\text{No. of months } S_{RR,t} \leq 69{,}600 \text{ ML occurred}}{\text{Average of } S_{RR,t}} \quad (5.22)$$

$$\text{Maximise}, f_{13} = Rel_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0}{n}\text{, where } n = 118 \text{ years} \quad (5.23)$$

$$\text{Maximise}, f_{14} = Res_{cons} = \frac{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) = 0 \text{ follows } (\sum_{t=1}^{12} Def_{cons,t}) > 0}{\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occured}} \quad (5.24)$$

$$\text{Minimise}, f_{15} = Vul_{cons} = \frac{(\sum_{t=1}^{12} Def_{cons,t})/\text{No. of years } (\sum_{t=1}^{12} Def_{cons,t}) > 0 \text{ occurred}}{\text{Average of } (\sum_{t=1}^{12} D_{cons,t})} \quad (5.25)$$

$$\text{Maximise}, f_{16} = Rel_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML}}{n}, \text{ where } n = 118 \text{ years} \quad (5.26)$$

$$\text{Maximise}, f_{17} = Res_{alloc} = \frac{\text{No. of years } W_{system,June} = 97{,}550 \text{ ML follows } W_{system,June} < 97{,}550 \text{ ML}}{\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}} \quad (5.27)$$

$$\text{Minimise}, f_{18} = Vul_{alloc} = \frac{(\Sigma(97{,}550 \text{ ML} - W_{system,June})/\text{No. of years } W_{system,June} < 97{,}550 \text{ ML occurred}}{\text{Average of } W_{system,June}} \quad (5.28)$$

Where, $t = \text{July, August, September, } \ldots\ldots, \text{June};$

Subject to the constraints as configured in the revised Wimmera-Glenelg REALM model (refer Section 3.3.2).

The decision variables to solve for are dv_1 to dv_{24} as specified in Table 5.1.

The above higher order MOOP (Run (A2)) is solved for five generations using the O-S modelling approach with the following optimisation parameters: population size (N) = 100, probability of crossover (p_c) = 0.8, and probability of mutation (p_m) = 0.2 (refer Section 3.4.2.2 for further details regarding the optimisation parameters adopted).

5.2.1.2 Run (A3) – The medium to high level GHG emission scenario

Run (A3) is the same as Run (A2) except that the climate and streamflow data used in Run (A3) correspond to the medium to high level GHG emissions. Note that there is a 16% reduction in the long term average annual availability of water under the medium to high GHG emission scenario compared to the historic hydro-climatic conditions. Refer to Section 5.2.2.3 for further details regarding the hydrological conditions under the medium to high GHG emission scenario. The reader is referred to Section 5.2.1.1 for details regarding the problem formulation and model setup.

5.2.2 Modelling results and discussion

5.2.2.1 Objective space

As explained for Run (A1) in Section 4.3.2.1, the O-S model was run for five generations and the population with the highest ranked SI operating plan under Run (A2) and Run (A3) were selected for analysis. The O-S model found a total of 54 and 53 optimal operating plans forming the Pareto front for Run (A2) and Run (A3) respectively. Note that a total of 56 optimal operating plans were found to form the Pareto front for Run (A1). Following the O-S modelling procedure, the dominance test was performed on the base case operating plan under the two GHG emission scenarios in order to determine its status with respect to the optimal plans found under Run (A2) and Run (A3) - refer Equation 2.2 for further details regarding the possible outcomes from the dominance test. As for the outcome under historic hydro-climatic conditions, the test concluded that the base case operating plan was not dominated by any of the optimal plans under Run (A3) and that the base case operating plan was optimal under medium to high level GHG emissions (and also under historic hydro-climatic conditions). However, the base case operating plan was dominated by one other optimal plan (i.e. Plan no. 8) under Run (A2) and so the base case operating plan was deemed to be inferior or not optimal under low to medium level GHG emissions.

Table 5.3 summaries the objective function (f) values, CI values, and SI values for the base case operating plan and Plan no. 8 under Run (A2). The results are organised in order of the objective functions and the corresponding CI, as follows:

- Objective functions, f_1 to f_3, represent the three environmental (env) interests for water expressed in terms of nil environmental flow deficits – refer to Equations 5.11 to 5.13;
- Objective functions, f_4 to f_{12}, represent the nine social ($socio$) interests for water expressed in terms of the volume held in Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR) – refer to Equations 5.14 to 5.22;
- Objective functions, f_{13} to f_{15}, represent the three consumptive ($cons$) interests for water expressed in terms of nil consumptive flow deficits – refer to Equations 5.23 to 5.25; and
- Objective functions, f_{16} to f_{18}, represent the three system-wide interests for water expressed in terms of water allocations ($alloc$) – refer to Equations 5.26 to 5.28.

The last row of Table 5.3 shows the SI values for the base case operating plan and Plan no. 8 under Run (A2) which are calculated from the four corresponding component-level indices (i.e. CI_{env}, CI_{socio}, CI_{cons}, and CI_{sys}). The shaded results represent the best outcome for each objective function, either in terms of the highest values for the those objective functions that were maximised (i.e. reliability and resiliency), or the lowest values of those objective functions that were minimised (i.e. vulnerability). Similarly, the shaded results for the CI and SI values are the best outcomes in terms of the highest values.

Table 5.3 Objective function values, Component-level Index values, and Sustainability Index values for the base case operating plan and Plan no. 8 under Run (A2)

Objective function (f_x), Component-level Index (CI_i), and Sustainability Index (SI)	Description	Values of f_x (%), CI_i (italic font), and SI (bold italic font)	
		Base case operating plan*	Run (A2) - Plan no. 8
$Max, f_1 = Rel_{env}$	Reliability of nil environmental flow deficits - Equation (5.7)	6%	6%
$Max, f_2 = Res_{env}$	Resiliency of nil environmental flow deficits - Equation (5.8)	4%	5%
$Min, f_3 = Vul_{env}$	Vulnerability of environmental flow deficits - Equation (5.9)	9%	8%
CI_{env}	*Environmental Component-level Index - Equation (5.1)*	*0.13*	0.14
$Max, f_4 = Rel_{LL}$	Reliability of volume at Lake Lonsdale exceeding 5,379 ML - Equation (5.10)	59%	63%
$Max, f_5 = Res_{LL}$	Resiliency of volume at Lake Lonsdale exceeding 5,379 ML - Equation (5.11)	12%	13%
$Min, f_6 = Vul_{LL}$	Vulnerability of volume at Lake Lonsdale falling below 5,379 ML - Equation (5.12)	34%	33%
$Max, f_7 = Rel_{LF}$	Reliability of volume at Lake Fyans exceeding 1,761 ML - Equation (5.13)	100%	100%
$Max, f_8 = Res_{LF}$	Resiliency of volume at Lake Fyans exceeding 1,761 ML - Equation (5.14)	100%	100%
$Min, f_9 = Vul_{LF}$	Vulnerability of volume at Lake Fyans falling below 1,761 ML - Equation (5.15)	0%	0%
$Max, f_{10} = Rel_{RR}$	Reliability of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (5.16)	83%	100%
$Max, f_{11} = Res_{RR}$	Resiliency of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (5.17)	11%	100%
$Min, f_{12} = Vul_{RR}$	Vulnerability of volume at Rocklands Reservoir falling below 69,600 ML - Equation (5.18)	17%	0%
CI_{socio}	*Social Component-level Index - Equation (5.2)*	*0.54*	0.73
$Max, f_{13} = Rel_{cons}$	Reliability of nil consumptive user deficits - Equation (5.19)	56%	62%
$Max, f_{14} = Res_{cons}$	Resiliency of nil consumptive user deficits - Equation (5.20)	50%	58%
$Min, f_{15} = Vul_{cons}$	Vulnerability of consumptive user deficits - Equation (5.21)	2%	1%
CI_{cons}	*Consumptive Component-level Index - Equation (5.3)*	*0.65*	0.71
$Max, f_{16} = Rel_{alloc}$	Reliability of full water allocations - Equation (5.22)	100%	100%
$Max, f_{17} = Res_{alloc}$	Resiliency of full water allocations - Equation (5.23)	100%	100%
$Min, f_{18} = Vul_{alloc}$	Vulnerability of reduced water allocations - Equation (5.24)	0%	0%
CI_{sys}	*System-wide Component-level Index - Equation (5.4)*	*1.00*	*1.00*
SI	***Sustainability Index - Equation (5.5)***	***0.49***	***0.58***

'f_x' refers to objective function x which is defined in Section 5.2.1.
'CI_i' refers to the Component-level Index for the i^{th} interest for water as defined in Section 5.1.
'SI' refers to the Sustainability Index for the Wimmera-Glenelg Water Supply System as defined in Equation 5.5.
* the base case operating plan is modelled by simulation-only under low-medium GHG emissions.
'Max, Min' refer to the maximisation or minimisation of f_x as defined in Equations 5.11 to 5.28.
'Rel, Res, Vul' refer to the reliability, resiliency, and vulnerability performance metrics respectively, as defined in Section 3.2.4.
'env' refers to environmental interests for water as defined in Section 3.2.3.1.
'LL, LF, RR' refer to social interests for water at Lake Lonsdale, Lake Fyans, and Rocklands Reservoir respectively, as defined in Section 3.2.3.2.
'$cons$' refers to consumptive interests for water as defined in Section 3.2.3.3.
'$alloc$' refers to system-wide interests for water as defined in Section 3.2.3.4.

Table 5.3 shows the reason that the base case operating plan is not optimal is due to Plan no. 8 being no worse than the base case operating plan in all objectives and better than it in at least one objective. In this case, Plan no. 8 is better than the base case operating plan in objectives f_2 to f_6, and f_{10} to f_{15}. Overall, the results show that Plan no. 8 provides a higher level of sustainability for the WGWSS, both individually for each of the four interests for water (in terms of CI) and collectively (in terms of SI).

Figure 5.2 shows the corresponding SI value against their respective normalised rank for the base case operating plan and for all the optimal operating plans under Run (A1), Run (A2), and Run (A3).

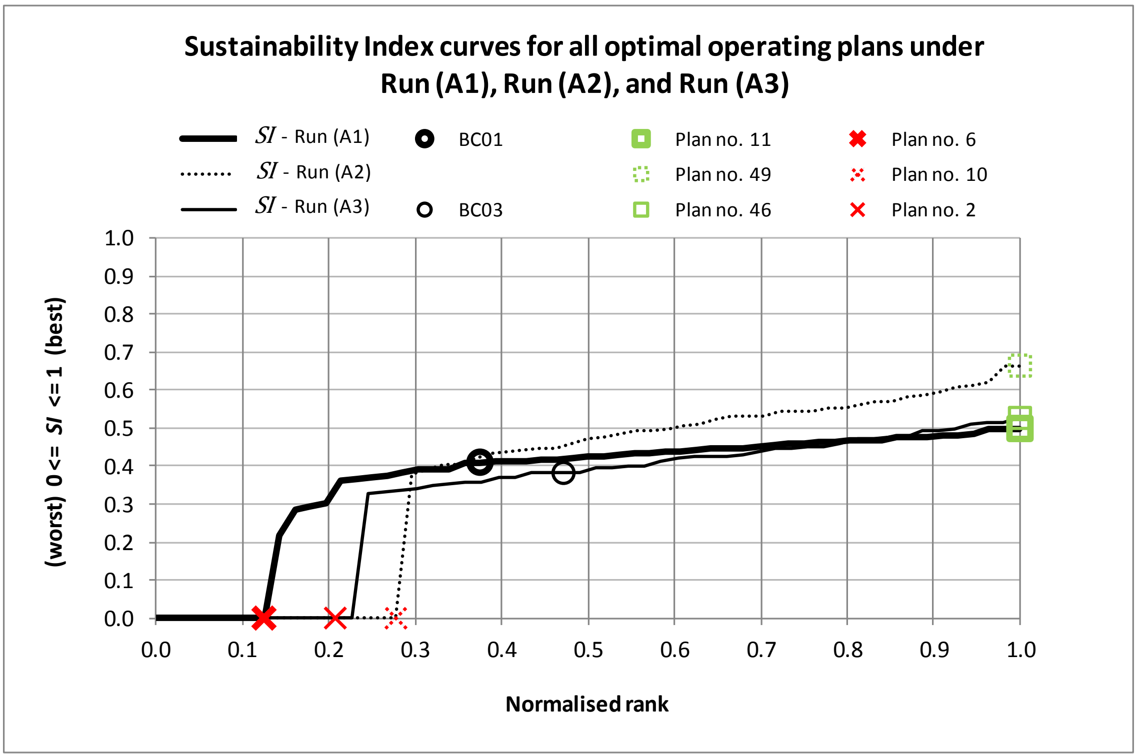


Figure 5.2 **Sustainability Index curves for all optimal operating plans under Run (A1), Run (A2), and Run (A3)**

The various attributes of the SI curves shown in Figure 5.2 are summarised as follows:

- Historic hydro-climatic conditions – the SI curve (shown with a thick black line), the base case operating plan (shown with a thick black open circle marker), the highest ranked SI operating plan under Run (A1) is Plan no. 11 (shown with a thick green square marker), and one of the lowest ranked SI operating plans under Run (A1) is Plan no. 6 (shown with a thick red cross marker);

- Low to medium level GHG emissions - the SI curve (shown with a dashed black line), the highest ranked SI operating plan under Run (A2) is Plan no. 49 (shown with a dashed green square marker), and one of the lowest ranked SI operating plans under Run (A2) is Plan no. 10 (shown with a dashed red cross marker). Note that the base case operating plan is not shown as it is not an optimal plan. The location of the optimal plan that dominates the base case operating plan is indicated by a red arrow (i.e. Plan no. 8 under Run (A2)); and
- Medium to high level GHG emissions - the SI curve (shown with a thin black line), the base case operating plan (shown with a thin black open circle marker), the highest ranked SI operating plan under Run (A3) is Plan no. 46 (shown with a thin green square marker), and one of the lowest ranked SI operating plans under Run (A3) is Plan no. 2 (shown with a thin red cross marker).

A comparison of the SI curves in Figure 5.2 highlights the effects of the two GHG emission scenarios on the sustainability of WGWSS (in terms of SI), as follows:

- The base case operating plans under historic hydro-climatic conditions and medium to high GHG emissions are neither the highest nor the lowest in terms of the level of sustainability that may be achieved in the WGWSS. The SI values are 0.41 under hydro-climatic conditions and 0.38 under medium to high GHG emissions.
- The SI values for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3) are 0.5, 0.66, and 0.53 respectively.
- Relative to the historic hydro-climatic conditions (i.e. Run (A1)), there is a similar level of increased diversity for those optimal operating plans which have SI values greater than zero under both GHG emission scenarios. This is evident by the increase in the gradient of the curves for Run (A2) and Run (A3), specifically for those optimal plans that have normalised rank values greater than 0.28 and 0.23 respectively.
- There are more optimal operating plans under the low to medium level GHG emissions scenario (i.e. Run (A2)) which achieve higher levels of sustainability than that under the medium to high level GHG emissions scenario (i.e. Run (A3)). This is evident by the 35% of optimal operating plans (or 19 out of 54

plans) under Run (A2) which have higher SI values than the highest SI value (of 0.53) under Run (A3).

- In terms of the lowest ranked SI operating plans (i.e. $SI = 0$), both GHG emission scenarios show an increase in the number of these optimal plans from the 12% of plans (i.e. 8 plans that have SI values of zero out of a total of 56 plans) under Run (A1) to the 27% of plans (i.e. 16 out of 54 plans) under Run (A2), and to the 22% of plans (i.e. 13 out of 53 plans) under Run (A3).

To facilitate comparisons among the base case operating plan and the highest ranked SI operating plans under the three hydro-climatic conditions, Plan no. 49 is tested for dominance under historic hydro-climatic conditions and under medium to high GHG emissions and Plan no. 46 is tested for dominance under historic hydro-climatic conditions and under low to medium GHG emissions. This potentially results in four optimal operating plans (i.e. base case operating plan, Plan no. 11, Plan no. 49, and Plan no. 46) for each of the three hydro-climatic conditions; a total of 12 plans subject to the outcomes of the dominance test (i.e. 4 plans $\times 3$ hydro-climatic scenarios $= 12$ plans). Note that the base case operating plan under low to medium GHG emissions is already known not to be optimal given the dominance test conducted earlier in Section 5.2.2.1. The motivation for these dominance tests is based on the notation that it would be practical (from an operational standpoint) to implement a robust optimal operating plan that is capable of withstanding a range of future climate scenarios. For the purposes of this investigation, a *robust* optimal operating plan is defined in this thesis by the following two conditions:

1. An operating plan that is optimal under all three hydro-climatic conditions. This first condition provides some certainty that one optimal plan is implemented over the planning period; and
2. An operating plan that achieves a higher level of sustainability for the WGWSS (in terms of SI) than the current level achieved under the base case operating plan. This condition provides some certainty that the sustainability of the WGWSS will not deteriorate over the planning period.

The results of the dominance tests for Plan no. 49 and Plan no. 46 confirm that both plans are optimal under all three hydro-climatic conditions.

Table 5.4 is a summary of the objective function (f) values, CI values, and SI values for the base case operating plan, Plan no. 11, Plan no. 49, and Plan no. 46 under the three hydro-climatic conditions. The results show the effects of the two GHG emission scenarios on the four interests for water (in terms of CI) and on the sustainability of WGWSS (in terms of SI). The results are tabulated using the same approach as explained earlier for Table 5.3, albeit that the shading of the best outcome in each case is colour-coded to align with the same hydro-climatic conditions (i.e. grey shade - historic hydro-climatic conditions, red shade - low to medium level GHG emissions, and green shade – medium to high level GHG emissions). Note that the results shown for the base case operating plan and Plan no. 11 under historic hydro-climatic conditions in Table 5.4 are the same as those shown in Table 4.6 and are repeated here for the reader's convenience.

In the interests of short listing robust optimal operating plans (as defined above) for selection by the DM in Section 5.3, the results for the base case operating plan, Plan no. 11, Plan no. 49, and Plan no. 46 are summarised as follows:

- The base case operating plan is not a robust optimal operating plan as it fails in terms of being an optimal plan under low to medium GHG emissions.
- Plan no. 11 is a robust optimal operating plan as it is optimal under all three hydro-climatic conditions and it achieves a higher level of SI than that achieved under the base case operating plan. Note that as the base case operating plan is not optimal under low to medium GHG emissions, it is not possible to compare it's SI to those operating plans which are optimal under low to medium GHG emissions. In this case, condition (1) above takes precedent over condition (2) and so comparisons with respect to SI are not applicable.
- Plan no. 49 and Plan no. 46 are robust optimal operating plans as these are optimal under all three hydro-climatic conditions and achieve a higher level of SI than the current levels achieved under the base case operating plan. As explained for Plan no. 11, condition (1) above takes precedent over condition (2) and so comparisons with respect to SI are not applicable. Note that the results for Plan no. 49 and Plan no. 46 are identical for all objective functions. The reason for the identical objective function values are investigated in Section 5.2.2.2.

Table 5.4 Objective function values, Component-level Index values, and Sustainability Index values for various operating plans under historic hydro-climatic conditions and two GHG emission scenarios

Objective function (f_x), Component-level Index (CI_i), and Sustainability Index (SI)	Description	Values of f_x (%), CI_i (italic font), and SI (bold italic font)											
		Historic hydro-climatic conditions				Low to medium GHG emissions				Medium to high GHG emissions			
		Base case operating plan*	Run (A1) - Plan no. 11	Plan no. 49*	Plan no. 46*	Base case operating plan*	Plan no. 11*	Run (A2) - Plan no. 49	Plan no. 46*	Base case operating plan*	Plan no. 11*	Plan no. 49*	Run (A3) - Plan no. 46
$Max, f_1 = Rel_{env}$	Reliability of nil environmental flow deficits - Equation (5.7)	25%	38%	59%	59%	na	14%	20%	20%	6%	11%	19%	19%
$Max, f_2 = Res_{env}$	Resiliency of nil environmental flow deficits - Equation (5.8)	16%	38%	40%	40%	na	15%	16%	16%	2%	10%	18%	18%
$Min, f_3 = Vul_{env}$	Vulnerability of environmental flow deficits - Equation (5.9)	10%	2%	5%	5%	na	3%	3%	3%	12%	4%	6%	6%
CI_{env}	*Environmental Component-level Index - Equation (5.1)*	*0.33*	*0.52*	*0.61*	*0.61*	*na*	*0.28*	*0.32*	*0.32*	*0.10*	*0.22*	*0.32*	*0.32*
$Max, f_4 = Rel_{LL}$	Reliability of volume at Lake Lonsdale exceeding 5,379 ML - Equation (5.10)	61%	92%	87%	87%	na	100%	91%	91%	50%	93%	74%	74%
$Max, f_5 = Res_{LL}$	Resiliency of volume at Lake Lonsdale exceeding 5,379 ML - Equation (5.11)	8%	3%	6%	6%	na	50%	24%	24%	11%	17%	11%	11%
$Min, f_6 = Vul_{LL}$	Vulnerability of volume at Lake Lonsdale falling below 5,379 ML - Equation (5.12)	26%	13%	17%	17%	na	2%	14%	14%	38%	11%	21%	21%
$Max, f_7 = Rel_{LF}$	Reliability of volume at Lake Fyans exceeding 1,761 ML - Equation (5.13)	99%	100%	100%	100%	na	100%	100%	100%	98%	100%	100%	100%
$Max, f_8 = Res_{LF}$	Resiliency of volume at Lake Fyans exceeding 1,761 ML - Equation (5.14)	33%	100%	100%	100%	na	100%	100%	100%	48%	100%	100%	100%
$Min, f_9 = Vul_{LF}$	Vulnerability of volume at Lake Fyans falling below 1,761 ML - Equation (5.15)	1%	0%	0%	0%	na	0%	0%	0%	2%	0%	0%	0%
$Max, f_{10} = Rel_{RR}$	Reliability of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (5.16)	86%	92%	92%	92%	na	100%	100%	100%	72%	95%	96%	96%
$Max, f_{11} = Res_{RR}$	Resiliency of volume at Rocklands Reservoir exceeding 69,600 ML - Equation (5.17)	2%	3%	4%	4%	na	100%	100%	100%	6%	14%	9%	9%
$Min, f_{12} = Vul_{RR}$	Vulnerability of volume at Rocklands Reservoir falling below 69,600 ML - Equation (5.18)	24%	17%	14%	14%	na	0%	0%	0%	21%	8%	7%	7%
CI_{socio}	*Social Component-level Index - Equation (5.2)*	*0.38*	*0.43*	*0.48*	*0.48*	*na*	*0.92*	*0.83*	*0.83*	*0.43*	*0.64*	*0.56*	*0.56*
$Max, f_{13} = Rel_{cons}$	Reliability of nil consumptive user deficits - Equation (5.19)	54%	69%	40%	40%	na	62%	37%	37%	43%	41%	29%	29%
$Max, f_{14} = Res_{cons}$	Resiliency of nil consumptive user deficits - Equation (5.20)	43%	51%	41%	41%	na	68%	29%	29%	27%	28%	21%	21%
$Min, f_{15} = Vul_{cons}$	Vulnerability of consumptive user deficits - Equation (5.21)	2%	3%	2%	2%	na	2%	2%	2%	2%	2%	2%	2%
CI_{cons}	*Consumptive Component-level Index - Equation (5.3)*	*0.61*	*0.70*	*0.54*	*0.54*	*na*	*0.74*	*0.47*	*0.47*	*0.48*	*0.48*	*0.39*	*0.39*
$Max, f_{16} = Rel_{alloc}$	Reliability of full water allocations - Equation (5.22)	94%	96%	96%	96%	na	100%	100%	100%	96%	100%	100%	100%
$Max, f_{17} = Res_{alloc}$	Resiliency of full water allocations - Equation (5.23)	14%	20%	20%	20%	na	100%	100%	100%	50%	100%	100%	100%
$Min, f_{18} = Vul_{alloc}$	Vulnerability of reduced water allocations - Equation (5.24)	36%	27%	23%	23%	na	0%	0%	0%	10%	0%	0%	0%
CI_{sys}	*System-wide Component-level Index - Equation (5.4)*	*0.44*	*0.52*	*0.53*	*0.53*	*na*	*1.00*	*1.00*	*1.00*	*0.76*	*1.00*	*1.00*	*1.00*
SI	*Sustainability Index - Equation (5.5)*	***0.41***	***0.50***	***0.52***	***0.52***	***na***	***0.74***	***0.66***	***0.66***	***0.38***	***0.55***	***0.53***	***0.53***

'f_x' refers to objective function x which is defined in Section 5.2.1.
'CI_i' refers to the Component-level Index for the i^{th} interest for water as defined in Section 5.1.
'SI' refers to the Sustainability Index for the Wimmera-Glenelg Water Supply System as defined in Equation 5.5.
* refers to operating plans that have been modelled under the given hydro-climatic conditions using simulation-only as distinct to plans that have been found by optimisation-simulation modelling
'na' means that the results for the operating plan are not applicable as the dominance test determined that the operating plan was not optimal
'Max, Min' refer to the maximisation or minimisation of f_x as defined in Equations 5.11 to 5.28.
'Rel, Res, Vul' refer to the reliability, resiliency, and vulnerability performance metrics respectively, as defined in Section 3.2.4.
'env' refers to environmental interests for water as defined in Section 3.2.3.1.
'LL, LF, RR' refer to social interests for water at Lake Lonsdale, Lake Fyans, and Rocklands Reservoir respectively, as defined in Section 3.2.3.2.
'$cons$' refers to consumptive interests for water as defined in Section 3.2.3.3.
'$alloc$' refers to system-wide interests for water as defined in Section 3.2.3.4.

Moreover, the results show that Plan no. 11 favours social and consumptive interests for water over environmental interests compared to the corresponding highest ranked SI operating plans found by the O-S model under both GHG emission scenarios. This is evident by the reduction in CI_{env} (e.g. Plan no. 49: $CI_{env} = 0.32$ cf. Plan no. 11: $CI_{env} = 0.28$) and the increase in CI_{socio} (i.e. Plan no. 49: $CI_{socio} = 0.83$ cf. Plan no. 11: $CI_{socio} = 0.92$) and CI_{cons} (i.e. Plan no. 49: $CI_{cons} = 0.47$ cf. Plan no. 11: $CI_{cons} = 0.74$) under low to medium GHG emissions. Furthermore, Plan no. 11 is not only optimal under all three hydro-climatic conditions, but it also achieves a higher SI value than those optimal plans that were found by the O-S model under the two GHG emission scenarios. The reason for these differences in the impact of GHG emissions on the interests for water and overall in terms of SI is discussed in Section 5.2.2.3.

5.2.2.2 Decision space

Table 5.5 to Table 5.10 summarise the results for the 24 decision variables (i.e. dv_1 to dv_{24}) in terms of their corresponding planning decision categories (refer to Table 5.1) for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3). Note that the robust optimal operating plans (as defined in Section 5.2.2.1) are Plan no. 11, Plan no. 49, and Plan no. 46 considering all three hydro-climatic conditions. The base case operating plan is included as a point of reference only as it is not a robust optimal operating plan.

Table 5.5 summarises the priority of supply planning decisions, dv_1 to dv_7. These priorities relate to the order in which water is sourced from different storages for supply to a water demand and also the order in which the different water demands are satisfied. The results show that Plan no. 49 and Plan no. 46 have more planning decisions in common with each other than those under Plan no. 11 (or the base case operating plan). For instance in terms of the number of priority of supply decisions, six out of seven of these planning decisions are in common between Plan no. 49 and Plan no. 46 (the exception being dv_5) compared to the four decisions in common between Plan no. 49 and Plan no. 11 (i.e. dv_3 to dv_5 and dv_7), and the three decisions in common between Plan no. 46 and Plan no. 11 (i.e. dv_3, dv_4 and dv_7).

Table 5.5 *Priority of supply* decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)

dv_x	Decisions	Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_1	Should Moora Moora Reservoir be the first priority of supply or Lake Wartook to demands (2) to (5) and EWDs in MacKenzie River (3) and Burnt Creek (4)?	Moora Moora Reservoir is first priority	Lake Wartook is first priority	Moora Moora Reservoir is first priority	
dv_2	Should Horsham (1) be supplied in preference to the EWD in MacKenzie River at Dad and Dave Weir (2) or vice versa?	EWD is satisfied first	Horsham is satisfied first	EWD is satisfied first	
dv_3	Should water be harvested into Taylors Lake in preference to meeting the EWD in MacKenzie River (3) or vice versa?	EWD is satisfied first			
dv_4	Should water be harvested into Taylors Lake in preference to meeting the EWD in Burnt Creek (4) or vice versa?	Flows harvested into Taylors Lake first	EWD is satisfied first		
dv_5	Should consumptive demands (6) to (9) be satisfied before the EWD in Glenelg River (1) or vice versa?	EWD is satisfied first	Consumptive demands are satisfied first		EWD is satisfied first
dv_6	Should water be harvested into Wimmera Inlet Channel (WIC) in preference to meeting passing flows in Wimmera River at Huddlestons Weir (6) or vice versa?	Provide passing flow first		Water harvested into WIC	
dv_7	Should water be held in storage for supply to consumptive demands (19) to (30) in preference to the EWD in Mt William Creek at Lake Lonsdale (5) or vice versa?	EWD is satisfied first	Held in storage for supply to consumptive demands first		

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
'EWDs' refers to environmental water demands.
Number in brackets refers to consumptive user demand centres and environmental flow sites shown in Figure 5.1.

Table 5.6 summarises the flood reserve volume planning decisions (i.e. dv_8) for the four optimal operating plans. Lake Wartook is operated to provide some degree of flood attenuation whilst at the same time ensuring a very good chance of filling over the winter/spring period. A large flood reserve volume may affect the supply to consumptive demands from the storage, while a small reserve volume may cause the storage to overflow more often and result in more water being lost (in an operational sense) from the system.

Table 5.6 ***Flood reserve volume*** **decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)**

dv_x	Decisions	Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_8	How much flood reserve should be provided at Lake Wartook in June?	8,807 ML	26,303 ML	27,605 ML	

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

The results for dv_8 show that the robust optimal operating plans have significantly larger flood reserve volumes compared to the base case operating plan. Two important observations are worth highlighting as follows:

- As explained in Section 4.4.2.2 with reference to Plan no. 11, the larger flood reserve volume of 26,303 ML was consistent with the higher priority of supply for Horsham (i.e. dv_2) even though this combination of planning decisions was not the same as that under the base case operating plan. However, under Plan no. 49 and Plan no. 46 there appears to be an inconsistency in that the larger flood reserve volume of 27,605 ML is accompanied by a higher priority of supply for the EWD in MacKenzie River at Dad and Dave Weir (i.e. dv_2). This combination of planning decisions under Plan no. 49 and Plan no. 46 places a greater risk to Horsham suffering an increased number and/or severity of consumptive user deficits during periods of water shortage (compared to Plan no. 11).
- Plan no. 49 and Plan no. 46 have the same flood reserve volume.

The reasons for both the above points are discussed in Section 5.2.2.3.

Table 5.7 compares the results for the planning decisions regarding the shares of environmental allocation in the WGWSS (i.e. dv_9 to dv_{11}). As explained in Section 4.4.2.2, the annual environmental allocation of 40,560 ML is released at four locations within the headworks, namely; the Glenelg River at Rocklands Reservoir (i.e. dv_9), MacKenzie River at Lake Wartook (i.e. dv_{10}), Mt William Creek at Lake Lonsdale (i.e. dv_{11}), and the Wimmera River at Taylors Lake.

Table 5.7 ***Share of environmental allocation*** **decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)**

dv_x	Decisions	Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_9	How much of the environmental water allocation should be released in the Glenelg River basin?	Up to 40% of the environmental water allocation	Up to 15% of the environmental water allocation	Up to 8% of the environmental water allocation	
dv_{10}	How much of the environmental water allocation should be released in the Wimmera basin at Lake Wartook?	Up to 30% of the remaining share of the environmental water allocation after that provided for the Glenelg basin	Up to 2% of the remaining share of the environmental water allocation after that provided for the Glenelg basin	Up to 22% of the remaining share of the environmental water allocation after that provided for the Glenelg basin	
dv_{11}	How much of the environmental water allocation should be released in the Wimmera basin at Lake Lonsdale?	Up to 60% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook	Up to 2% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook	Up to 19% of the remaining share of the environmental water allocation after that provided for the Glenelg basin and that at Lake Wartook	

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

Note that the Taylors Lake environmental allocation share is not included in Table 5.7, as it is by default the remaining share of the environmental allocation after that provided at Rocklands Reservoir, Lake Wartook, and Lake Lonsdale. The results for dv_9 to dv_{11} show that the environmental allocation shares under the robust optimal operating plans represent a significant change from the base case operating plan. For instance in terms of the Glenelg basin shares (dv_9), there is a major shift of environmental allocation from the Glenelg basin to the Wimmera basin (i.e. 40% under the base case operating plan to 8% under Plan no. 49 and Plan no. 46). The results for dv_{10} and dv_{11} also show that the robust optimal operating plans have markedly different shares at Lake Wartook and Lake Lonsdale respectively. Interestingly, the results for the environmental allocation shares show a similar pattern to that observed in the flood reserve volume planning decisions (i.e. dv_8), in terms of the way Plan no. 11 differs from the planning decisions made under Plan no. 49 and Plan no. 46:

- As explained in Section 4.4.2.2 with reference to Plan no. 11, the larger flood reserve volume of 26,303 ML was consistent with the smaller environmental allocation share at Lake Wartook (i.e. dv_{10}) even though this combination of planning decisions was not the same as that under the base case operating plan. The consistency occurred given that the larger flood reserve volume would increase the volume of water released to the MacKenzie River and Burnt Creek downstream and provide more water for EWDs than that under the base case operating plan. This would have the effect of reducing the environmental allocation share at Lake Wartook under Plan no. 11 compared to that under the base case operating plan. However, under Plan no. 49 and Plan no. 46 there appears to be an inconsistency in that the larger flood reserve volume of 27,605 ML is accompanied by a large environmental allocation share at Lake Wartook (i.e. dv_{10}). This combination of planning decisions under Plan no. 49 and Plan no. 46 places a greater risk to Horsham in addition to that which would already occur given the higher priority of supply for the EWD in MacKenzie River at Dad and Dave Weir (i.e. dv_2) as mentioned earlier.
- Plan no. 49 and Plan no. 46 have the same environmental allocation shares at all four sites.

In contrast to the above observations, there appears to be consistency among the robust optimal operating plans with respect to holding water in Lake Lonsdale for supply to consumptive demands (i.e. dv_7) together with the increased environmental allocation share at Taylors Lake compared to the base case operating plan. It is noted however that unlike that under Plan no. 11 which has a negligible share at Lake Lonsdale (i.e. dv_{11}), the results for Plan no. 49 and Plan no. 46 show that the storage would continue to play a role in supplying EWDs similar to that under the base case operating plan, albeit with a smaller environmental allocation share.

Table 5.8 compares the results for the flow path planning decisions (i.e. dv_{12} and dv_{13}). Decision variable dv_{12} provides a flow path for resources in the eastern parts of the WGWSS to supply EWDs in the Wimmera River and consumptive demands via the Wimmera Mallee Pipeline. These resources include catchment flows intercepted by Fyans Creek and Mt William Creek and water held in Lake Bellfield, Lake Fyans and Lake Lonsdale. Decision variable dv_{13} relates to the maintenance of water quality in terms of the mixing of water sourced from Lake Bellfield with that sourced from the Wimmera River via Taylors Lake.

Table 5.8 *Flow path* decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)

dv_x	Decisions	Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_{12}	Should Mt William Creek flows be harvested into Wimmera Inlet Channel or should all these flows be passed down to Wimmera River?	Harvesting of flows into Wimmera Inlet Channel is allowed			
dv_{13}	Should water from Lake Bellfield be mixed with water from Taylors Lake via the Bellfield-Taylors Pipeline?	Yes, in a proportion based on the volume in Lake Bellfield	No mixing via the Bellfield-Taylors Pipeline*		

'dv_x' refers to decision variable x which are defined in Section 3.3.2.
* Mixing of water from Lake Bellfield and Taylors Lake can still occur provided that dv_{12} allows for harvesting of flows into Wimmera Inlet Channel.

The results for dv_{12} show that the base case operating plan and the robust optimal operating plans harvest Mt William Creek flows into the Wimmera Inlet Channel. However, in the case of dv_{13} the results show a significant change in terms of the flow path used to transfer water from Lake Bellfield to Taylors Lake. Whilst this differs from the manner in which the two storages operate, this decision is consistent with holding water in Lake Lonsdale for supply to meet consumptive demands via the Wimmera Mallee Pipeline (i.e. dv_7). In essence, this would mean that Lake Bellfield would make more water transfers to Lake Lonsdale for consumptive supply purposes rather than using the Bellfield-Taylors Pipeline (as is currently the case shown under the base case operating plan). The implications of such changes were discussed in Section 4.4.2.3. Again, as observed in the flood reserve volume at Lake Wartook (i.e. dv_8) and in the environmental allocation shares (i.e. dv_9 to dv_{11}) under Plan no. 49 and Plan no. 46, the O-S model adopted the same decision variable values for dv_{12} and dv_{13}. The reason for the O-S model adopting the same values under both runs is explained in Section 5.2.2.3.

Table 5.9 and Table 5.10 summarise the planning decisions relating to storage maximum operating volumes (i.e. dv_{14} to dv_{20}) and storage drawdown priorities and storage targets (i.e. dv_{21} to dv_{24}) respectively. Interestingly, identical results occur under Plan no. 49 and Plan no. 46 for dv_{14} to dv_{24}. Note that with respect to all planning decisions, this pattern occurs for consecutive decision variables from dv_{6} to dv_{24}. The reason for the O-S model adopting the same values under both runs is explained in Section 5.2.2.3. It is also worth highlighting that Taylors Lake is the only storage that has higher storage maximum operating volumes under Plan no. 11, Plan no. 49, and Plan no. 46 compared to the base case operating plan. This is indicative of increased harvesting of unregulated flow from the Wimmera River at Taylors Lake to compensate for the decreased harvesting at the other storages (by virtue of their lower storage maximum operating volumes).

Table 5.9 ***Storage maximum operating volume (MOV)*** **decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)**

dv_x	Decisions	Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_{14}	Toolondo Reservoir MOV	92,430 ML	46,215 ML	36,972 ML	
dv_{15}	Lake Lonsdale MOV	Inlet is closed		Inlet is open	
dv_{16}	Lake Bellfield MOV	76,000 ML	30,400 ML	45,600 ML	
dv_{17}	Taylors Lake MOV	26,960 ML	30,330 ML	26,960 ML	
dv_{18}	Rocklands Reservoir MOV	261,000 ML	208,800 ML	243,600 ML	
dv_{19}	Lake Lonsdale MOV	53,300 ML	52,000 ML	32,500 ML	
dv_{20}	Moora Moora Reservoir MOV	6,300 ML	2,520 ML	4,410 ML	
Total storage maximum operating volume		*515,990 ML*	*370,265 ML*	*390,042 ML*	

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

Table 5.10 ***Storage draw down priority and storage target*** **decisions for the base case operating plan and for the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3)**

dv_x	Decisions		Base case operating plan	Run (A1) – Plan no. 11	Run (A2) – Plan no. 49	Run (A3) – Plan no. 46
dv_{21}	What should be the drawdown priority of the headworks storages?	Lake Wartook	2nd	6th	5th	
		Moora Moora Reservoir	1st	4th	1st	
		Horsham storages	3rd	2nd	3rd	
		Rocklands Reservoir	8th	8th	7th	
		Toolondo Reservoir	4th	7th	2nd	
		Lake Bellfield	6th	3rd	4th	
		Lake Fyans	7th	5th	6th	
		Taylors Lake	5th	1st	8th	
dv_{22}	What should be the second point on the target curve for the headworks storages?	Lake Wartook	10,000 ML	8,790 ML	26,370 ML	
		Moora Moora Reservoir	2,000 ML	5,040 ML	5,670 ML	
		Horsham storages	328 ML	66 ML	197 ML	
		Rocklands Reservoir	69,540 ML	174,000 ML	313,200 ML	
		Toolondo Reservoir	5,000 ML	9,243 ML	18,486 ML	
		Lake Bellfield	10,000 ML	23,568 ML	31,424 ML	
		Lake Fyans	2,500 ML	9,230 ML	1,846 ML	
		Taylors Lake	8,500 ML	5,420 ML	21,680 ML	
	Total volume for second point on target curve		*107,868 ML*	*235,357 ML*	*418,873 ML*	
dv_{23}	What should be the third point on the target curve for the headworks storages?	Lake Wartook	29,300 ML	27,249 ML	27,835 ML	
		Moora Moora Reservoir	6,300 ML	5,922 ML	5,922 ML	
		Horsham storages	328 ML	249 ML	302 ML	
		Rocklands Reservoir	115,900 ML	330,600 ML	327,120 ML	
		Toolondo Reservoir	46,250 ML	50,837 ML	77,641 ML	
		Lake Bellfield	20,000 ML	51,064 ML	45,565 ML	
		Lake Fyans	10,000 ML	16,614 ML	16,799 ML	
		Taylors Lake	8,500 ML	11,924 ML	23,306 ML	
	Total volume for third point on target curve		*236,578 ML*	*494,459 ML*	*524,489 ML*	
dv_{24}	What should be the fourth point on the target curve for the headworks storages?	Lake Wartook	29,300 ML	28,685 ML	28,275 ML	
		Moora Moora Reservoir	6,300 ML	6,187 ML	5,998 ML	
		Horsham storages	328 ML	257 ML	320 ML	
		Rocklands Reservoir	260,775 ML	334,080 ML	333,384 ML	
		Toolondo Reservoir	46,250 ML	84,111 ML	80,599 ML	
		Lake Bellfield	78,560 ML	75,810 ML	55,463 ML	
		Lake Fyans	10,000 ML	18,091 ML	17,463 ML	
		Taylors Lake	8,500 ML	25,582 ML	24,444 ML	
	Total volume for fourth point on target curve		*440,013 ML*	*572,803 ML*	*545,946 ML*	

'dv_x' refers to decision variable x which are defined in Section 3.3.2.

The results in Table 5.9 and Table 5.10 show that there is consistency amongst the robust optimal operating plans in that compared to the base case operating plan these plans have lower total storage maximum operating volumes and higher storage target volumes. Whilst the results for the storage drawdown priorities cannot be structured in the same way as the storage maximum operating volumes and storage targets, the results show that the priorities under the robust optimal operating plans would be different from those under the base case operating plan.

Whilst there is consistency between these planning decisions (i.e. storage maximum operating volumes, storage drawdown priorities, and storage targets) and other relevant planning decisions under Plan no. 11 (as explained in Section 4.4.2.2), the same is not apparent from the decisions under Plan no. 49 and Plan no. 46. For example in the case of Rocklands Reservoir:

- It was explained that the decrease in the storage maximum operating volume at Rocklands Reservoir (i.e. dv_{18}) from 261,000 ML under the base case operating plan to 208,800 ML under Plan no. 11 had the effect of forcing water out of the storage and so satisfying the downstream EWD at the risk of not satisfying the consumptive demands (refer to consumptive users (6) to (9) in Figure 5.1). This planning decision was consistent with placing higher priority in supplying consumptive demands from Rocklands Reservoir over the EWD in the Glenelg River under Plan no. 11 (i.e. dv_5). However, under Plan no. 49 and Plan no. 46 the smaller reduction in the storage maximum operating volume at Rocklands Reservoir from 261,000 ML under the base case operating plan to 243,600 ML results in different priorities placed between supplying the consumptive demands and EWD (i.e. dv_5). The reason for the O-S model adopting the different priorities of supply is explained in Section 5.2.2.3; and
- It was explained that the increase in storage targets at Rocklands Reservoir for the second point (i.e. from 69,540 ML under the base case operating plan to 174,000 ML under Plan no. 11, dv_{22}), for the third point (i.e. from 115,900 ML under the base case operating plan to 330,600 ML under Plan no. 11, dv_{23}), and the fourth point (i.e. from 260,775 ML under the base case operating plan to 334,080 ML under Plan no. 11, dv_{24}) had the effect of increasing the rate of harvest at Rocklands Reservoir. Such planning decisions were required in order to satisfy the EWD in the Glenelg River by compensating for the reduced

share of environmental allocation under Plan no. 11 (i.e. dv_9). The same pattern, albeit to a greater extent, occurs under Plan no. 49 and Plan no. 46, particularly for the second point (i.e. from 69,540 ML under the base case operating plan to 313,200 ML under Plan no. 49 and Plan no. 46, dv_{22}).

In summary, the results for the robust optimal operating plans (i.e. dv_1 to dv_{24}) show that 21 out of 24 planning decisions under Plan no. 11; 20 out of 24 planning decisions under Plan no. 49; and 19 out of 24 planning decisions under Plan no. 46 are different from those under the base case operating plan. Interestingly, all but one of the 24 planning decisions (i.e. dv_5) are identical under Plan no. 49 and Plan no. 46. The reason for the O-S model adopting different priorities of supply for the consumptive demands from Rocklands Reservoir and the EWD in the Glenelg River is explained in Section 5.2.2.3.

5.2.2.3 Discussion

The analysis of the base case operating plan and the highest ranked SI operating plans under three hydro-climatic conditions in Sections 5.2.2.1 and 5.2.2.2 raised the following points for further discussion:

- The CI and SI results for Plan no. 49 and Plan no. 46 were identical under all three hydro-climatic conditions (refer to Table 5.4). This was shown to be consistent with both plans having the same decision variable values for all but one of the 24 planning decisions (i.e. dv_5). Note that decision variable dv_5 relates to the priority of supply between the consumptive demands from Rocklands Reservoir and the EWD in the Glenelg River (downstream of the storage). However, it was not apparent from the (objective space and decision space) results presented as to the reason for this difference in dv_5 other than that the plans were found under two separate O-S model runs, each of which assumed a different GHG emission scenario (i.e. Plan no. 49 was the highest ranked SI operating plan found under low to medium GHG emissions and Plan no. 46 was the highest ranked SI operating plan found under medium to high GHG emissions).
- The SI value for Plan no. 11, the highest ranked SI operating plan found by the O-S model under historic hydro-climatic conditions, was higher than the corresponding highest ranked SI operating plans that were found under both

GHG emission scenarios. It is important to highlight that the reason for this occurrence is due to the limited number of generations which were used in the O-S modelling procedure (i.e. 5 generations). Whilst it has not been confirmed in this thesis, it is expected that with the use of parallel processing and higher computational processing power, a greater number of modelling generations would have found operating plans with SI values greater than their Plan no. 11 counterparts, under both GHG emission scenarios. Nevertheless a comparison of Plan no. 49 and Plan no. 46 revealed that Plan no. 11 favoured social and consumptive interests for water over environmental interests. Whilst the results in the objective space did not provide any supporting information for this occurrence, there appears to be some explanation provided by certain differences in the decision variable values among the three robust optimal operating plans (i.e. Plan no. 11, Plan no. 49, and Plan no. 46). For instance, it was explained that the inconsistency in the planning decisions regarding the operation of Lake Wartook (i.e. dv_2, dv_8 and dv_{10}) and Rocklands Reservoir (i.e. dv_5 and dv_{18}) may adversely impact consumptive user demands and as a consequence provide favourable conditions for EWDs under Plan no. 49 and Plan no. 46. However, the results presented were not able to confirm whether it was Lake Wartook or Rocklands Reservoir, or both storages that caused a reduction in the social and consumptive interests for water over an improvement in environmental interests under Plan no. 49 and Plan no. 46.

Both the above points highlight the importance of using simulation modelling in order to emulate the behaviour of the system under the effect of unproven optimal operating plans, particularly those plans which consider future GHG emission scenarios. This simulation modelling output can be used to provide the DM with a more detailed appreciation of the impacts (beyond that provided by the performance metrics alone) without any risk to human life, ecological health, and the water resources of the WGWSS. Table 5.11 is a summary of the simulation modelling outputs for the base case operating plan and the highest ranked SI operating plans presented thus far in terms of a water balance for the WGWSS. A water balance is a holistic summary of the effects of the three hydro-climatic conditions on different parts of the WGWSS over the entire planning period (i.e. the availability of surface water in the various streams referred to as 'inflow' and also the water that leaves the system referred to as 'outflow').

Table 5.11 Water balance for operating plans under historic hydro-climatic conditions and two GHG emission scenarios – ML/year

Inflows and outflows of the Wimmera-Glenelg Water Supply System (Note: Total inflow equals total outflow)		Historic hydro-climatic conditions				Low to medium GHG emissions				Medium to high GHG emissions			
		Base case operating plan*	Run (A1) - Plan no. 11	Plan no. 49*	Plan no. 46*	Base case operating plan*	Plan no. 11*	Run (A2) - Plan no. 49	Plan no. 46*	Base case operating plan*	Plan no. 11*	Plan no. 49*	Run (A3) - Plan no. 46
Inflow[1]:	Glenelg River	102,552	102,552	102,552	102,552	92,028	92,028	92,028	92,028	91,284	91,284	91,284	91,284
	Wannon River	15,936	15,936	15,936	15,936	11,004	11,004	11,004	11,004	9,780	9,780	9,780	9,780
	Total Glenelg basin:	*118,488*	*118,488*	*118,488*	*118,488*	*103,032*	*103,032*	*103,032*	*103,032*	*101,064*	*101,064*	*101,064*	*101,064*
	Wimmera River	98,412	98,412	98,412	98,412	86,184	86,184	86,184	86,184	81,492	81,492	81,492	81,492
	Mt William Creek	73,200	73,200	73,200	73,200	72,504	72,504	72,504	72,504	68,100	68,100	68,100	68,100
	Fyans Creek	28,740	28,740	28,740	28,740	23,592	23,592	23,592	23,592	21,972	21,972	21,972	21,972
	McKenzie River and Burnt Creek	37,668	37,668	37,668	37,668	30,648	30,648	30,648	30,648	27,924	27,924	27,924	27,924
	other minor streams[2]	4,764	4,764	4,764	4,764	3,588	3,588	3,588	3,588	3,684	3,684	3,684	3,684
	Total Wimmera basin:	*242,784*	*242,784*	*242,784*	*242,784*	*216,516*	*216,516*	*216,516*	*216,516*	*203,172*	*203,172*	*203,172*	*203,172*
	Total inflow:	**361,272**	**361,272**	**361,272**	**361,272**	**319,548**	**319,548**	**319,548**	**319,548**	**304,236**	**304,236**	**304,236**	**304,236**
Consumptive use[3]:	Users (1) to (5)	6,672	6,503	6,442	6,442	6,528	6,360	6,216	6,216	5,784	5,844	5,592	5,592
	Users (6) to (9)	6,314	6,734	6,470	6,470	6,804	6,792	6,648	6,648	6,785	6,817	6,673	6,673
	Users (10) to (18)	4,176	4,212	4,200	4,200	4,176	4,164	4,140	4,140	4,164	4,176	4,152	4,152
	Users (19) to (30)	33,312	33,640	32,560	32,560	34,308	34,464	33,984	33,984	34,104	34,343	33,924	33,924
	Total consumptive use:	*50,474*	*51,089*	*49,672*	*49,672*	*51,816*	*51,780*	*50,988*	*50,988*	*50,837*	*51,180*	*50,341*	*50,341*
Headworks loss:	Eastern section[4]	22,556	32,639	28,223	28,223	26,404	39,961	33,400	33,400	23,939	36,949	30,017	30,017
	Central section[5]	10,948	9,086	10,532	10,532	10,592	9,920	10,111	10,111	9,786	9,038	9,395	9,395
	Western section[6]	28,433	27,607	30,167	30,167	37,560	46,537	48,400	48,400	38,834	45,406	47,897	47,897
	Total headworks loss:	*61,937*	*69,332*	*68,922*	*68,922*	*74,556*	*96,419*	*91,910*	*91,910*	*72,559*	*91,393*	*87,308*	*87,308*
Environmental flow (regulated)[7]:	EWD (1)	*6,619*	*3,451*	*2,395*	*2,395*	*11,977*	*5,371*	*3,140*	*3,140*	*13,078*	*5,626*	*3,182*	*3,182*
	EWDs (2) to (4)	-	-	-	-	-	-	-	-	-	-	-	-
	EWDs (5) and (6)	*6,205*	*569*	*3,284*	*3,284*	*12,070*	*738*	*5,545*	*5,545*	*10,732*	*733*	*5,573*	*5,573*
	Total environmental flow (regulated):	*12,824*	*4,020*	*5,680*	*5,680*	*24,047*	*6,109*	*8,686*	*8,686*	*23,809*	*6,359*	*8,755*	*8,755*
Environmental flow (unregulated)[8]:	EWD (1)	56,562	60,575	51,234	51,234	33,725	30,858	25,681	25,681	31,406	32,045	27,329	27,329
	EWDs (2) to (4)	23,874	19,903	20,809	20,809	17,293	14,324	15,869	15,869	15,955	13,532	14,548	14,548
	EWDs (5) and (6)	141,687	144,437	153,255	153,255	109,198	111,638	118,169	118,169	101,759	102,400	108,666	108,666
	Wannon River	12,526	10,270	10,271	10,271	7,777	6,781	6,781	6,781	7,050	6,031	6,031	6,031
	other minor streams	3,688	3,817	3,534	3,534	2,628	2,734	2,561	2,561	2,767	2,858	2,731	2,731
	Total environmental flow (unregulated):	*238,336*	*239,002*	*239,103*	*239,103*	*170,622*	*166,335*	*169,061*	*169,061*	*158,937*	*156,867*	*159,305*	*159,305*
Change in storage:		-2,300	-2,171	-2,104	-2,104	-1,492	-1,095	-1,097	-1,097	-1,907	-1,563	-1,474	-1,474
	Total outflow:	**361,272**	**361,272**	**361,272**	**361,272**	**319,548**	**319,548**	**319,548**	**319,548**	**304,236**	**304,236**	**304,236**	**304,236**

* refers to operating plans that have been modelled under the given hydro-climatic conditions using simulation-only as distinct to plans that have been found by optimisation-simulation modelling

1. 'Inflow' refers storage inflows and overland or catchment flows intercepted by streams and open channels within the Wimmera-Glenelg Water Supply System
2. Inflow to Langi Ghiran, Mt Cole, and Panrock reservoirs
3. 'Consumptive use' refers to consumptive users (1) to (30) as shown in Figure 5.1.
4. The storages, open channels and pipelines that are used to transfer water from Lake Bellfield to Lake Fyans and to Lake Lonsdale, and from Lake Fyans to Lake Lonsdale
5. The storages, open channels and pipelines that are used to transfer water from Moora Moora Reservoir to environmental water demands (3), and from Lake Wartook to Horsham Reservoir and to environmental water demands (2) to (4)
6. The storages, open channels and pipelines that are used to transfer water from Rocklands Reservoir to Toolondo Reservoir and to Taylors Lake
7. 'Environmental flow (regulated)' refers to water that is released from storage to meet environmental water demands or EWDs (1) to (6) as shown in Figure 5.1.
8. 'Environmental flow (unregulated)' refers to run-of-river flows that contribute to environmental water demands or EWDs (1) to (6) as shown in Figure 5.1 including spills at Wannon River diversion and minor storage spills at Langi Ghiran, Mt Cole, and Panrock reservoirs

For instance, compared to the historic hydro-climatic conditions the results show that there is a 12% reduction in the availability of water under the low to medium GHG emission scenario (i.e. $1-(\frac{319{,}548}{361{,}272})$) and a 16% reduction under the medium to high GHG emission scenario (i.e. $1-(\frac{304{,}236}{361{,}272})$). Moreover, the results show that the reduction is varied among the streams compared to historic hydro-climatic conditions. Using this same approach, the Glenelg basin would experience reductions of 13% and 15% under low to medium and medium to high GHG emissions respectively. In contrast, the Wimmera basin would experience reductions of 11% and 16% under low to medium and medium to high GHG emissions respectively.

The effect of the three hydro-climatic conditions is also shown in terms of the outflows from the WGWSS. Table 5.11 provides a breakdown of the various consumptive users and environmental water demands (EWDs) as shown in Figure 5.1, and headworks loss in terms of the storage evaporation and transmission losses that would occur in the eastern, central, and western parts of the WGWSS. Compared to the average of the total consumptive use across the four operating plans under the historic hydro-climatic conditions (i.e. $\frac{50{,}474+51{,}089+49{,}672+49{,}672}{4}=50{,}227\text{ ML}$), the results show that the average annual consumptive use volume increases by 2% (i.e. $1-(\frac{51{,}816+51{,}780+50{,}988+50{,}988}{50{,}227})$) and 1% (i.e. $1-(\frac{50{,}837+51{,}180+50{,}341+50{,}341}{50{,}227})$) under low to medium and medium to high GHG emissions respectively. Using this same approach, the average of the total headworks loss across the four operating plans increases by 32% and 26% under low to medium and medium to high GHG emissions respectively. Interestingly, the base case operating plan has the lowest total headworks loss compared to the other plans under each of the three hydro-climatic conditions.

In terms of the releases from storage to the EWDs, the results show that the average of the total environmental flow (regulated) across the four operating plans increases by 69% under the two GHG emission scenarios and that this is largely attributed to the base case operating plan. In fact, the results show that compared to the base case operating plan, the other plans would cause a significant reduction in the total environmental flow (regulated) compared to a small change in the total consumptive use under each of the three hydro-climatic conditions. The implications of this disproportionate impact between consumptive users and the regulated environmental flows are discussed later in Section 5.2.2.3. It is also worth highlighting that compared to the base case operating plan, the change in total environmental flows (regulated) and the change in total consumptive use differs for Plan no. 11 and both Plan no. 49 and Plan no. 46. The results show that under all three hydro-climatic conditions, Plan no. 11 supplies more water on average to consumptive use and less water to regulated environmental flows compared to Plan no. 49 and Plan no. 46. These changes in the regulated environmental flows and consumptive use volumes are discussed later in Section 5.2.2.3. Whilst the results show an increase in the average of the total environmental flow (regulated) across the four operating plans, the run-of-river in the WGWSS would experience a significant decline under the GHG emissions scenarios. Compared to the average of the total environmental flows (unregulated) across the four operating plans under the historic hydro-climatic conditions, the results show that there would be a decrease of 29% and 34% under low to medium and medium to high GHG emissions respectively.

It is important to highlight that the level of aggregation of the various inflows and outflows of the water balance has been tailored for the purposes of providing a direct response to the two points of discussion mentioned earlier in Section 5.2.2.3. Thus, the O-S modelling results (i.e. Sections 5.2.2.1 and 5.2.2.2) together with the supporting information provided by the simulation modelling outputs (i.e. Table 5.11), provide the following explanation for these two points of discussion:

- The first point of discussion was in relation to the different dv_5 values under Plan no. 49 and Plan no. 46 representing the priority of supply between the consumptive demands from Rocklands Reservoir and the EWD in the Glenelg River (refer to consumptive users (6) to (9) and EWD (1) in Figure 5.1). As explained in Section 3.2.3.2, in addition to Rocklands Reservoir serving as an important source of water to consumptive users (6) to (9) and EWD (1) it also supports the entire WGWSS by holding the majority of carryover water, reserve for following year, and water to users in the Wimmera basin either through direct supplies or by substitution with local sources of supply (i.e. consumptive users (1) to (5) and (10) to (30)). This means that dv_5 is influenced by the availability of water in both the Glenelg River and Wimmera basin. The results in Table 5.11 show that the decline in the availability of water in the Glenelg River relative to historic hydro-climatic conditions is 10% (i.e. $1-(\frac{92{,}028}{102{,}552})$) and 11% (i.e. $1-(\frac{91{,}284}{102{,}552})$) compared to a decline in the Wimmera basin of 11%

(i.e. $1 - (\frac{216,516}{242,784})$) and 16% (i.e. $1 - (\frac{203,172}{242,784})$) under low to medium and medium to high GHG emissions respectively. On this basis, it would appear that the larger reduction in the Wimmera basin under medium to high GHG emissions (i.e. 16%) is consistent with adopting a higher priority for the EWD in the Glenelg River in order to ensure that environmental flows are provided water first before consumptive users under Plan no. 46. Despite this reasoning, the simulation modelling results for Plan no. 49 under medium to high GHG emissions confirm that dv_5 is not sensitive to the decline in water availability (caused by the GHG emissions) given that the results are the same as the O-S modelling results for Plan no. 46 under the same GHG emission scenario. Note that the same effect is observed in the simulation modelling results for Plan no. 46 under low to medium GHG emissions compared to the O-S modelling results for Plan no. 49 under the same GHG emission scenario.

- The second point of discussion was in relation to the way in which the impacts of the GHG emissions were shared amongst the four interests for water (i.e. environmental, social, consumptive, and system-wide interests). Compared to Plan no. 49 and Plan no. 46, the CI results showed that Plan no. 11 favoured social and consumptive interests for water over environmental interests (refer to Table 5.4). The average annual volumes for consumptive users (1) to (30) under Plan no. 11 are consistently higher than those under Plan no. 49 and Plan no. 46 for all three hydro-climatic conditions (refer to Table 5.11). This confirms that the higher consumptive use volumes under Plan no. 11 would occur across the whole WGWSS and not be localised solely around Lake Wartook and Rocklands Reservoir as the planning decision results indicated in Section 5.2.2.2. Moreover, the average annual headworks loss volumes in the eastern section (which are largely attributed to Lake Lonsdale) are consistently higher under Plan no. 11 indicating that the eastern storages would be holding more water than that under Plan no. 49 and Plan no. 46. Note that this is confirmed by the better performing objective functions for Lake Lonsdale (i.e. higher f_4 and f_5 values and the lower f_6 value) under Plan no. 11 compared to those under Plan no. 49 and Plan no. 46 under the GHG emission scenarios (refer to Table 5.4).

It is worth noting that in Victoria (Australia) a decline in the long-term availability of water which has a disproportionate effect on the environment or on consumptive use may trigger a review of the long-term water resources to determine the actions required to restore the balance between the environment and consumptive use (Section 22P of the *Water Act 1989* (Vic)). In the context of the disproportionate impact between consumptive users and environmental flows discussed earlier, it would be prudent to explicitly account for such disproportionality in the formulation of higher order MOOPs in order to guide the optimisation search towards more equitable solutions.

Moreover, the water balance results for the base case operating plan raise another important point in regards to the formulation of the MOOPs presented. In comparison to the robust optimal operating plans, the results in Table 5.11 suggest that the base case operating plan is a viable alternative plan in terms of it consistently providing (i) similar consumptive use volumes; (ii) the lowest volumes of headworks loss; and (iii) the highest total (regulated and unregulated) environmental flow volumes under the three hydro-climatic conditions. This highlights the importance of properly formulating the MOOP to represent all interests for water including operational efficiency which could have been expressed as a system-wide interest for water in substitution for (or addition to) users' water allocations. The corresponding objective function would have minimised the volume of headworks loss and potentially have guided the optimisation search towards more efficient modes of operation; thus finding optimal operating plans that dominated the base case operating plan.

It is important at this point to refer to a recent review of the operation of the WGWSS (using a REALM simulation modelling approach) which showed that the base case operating plan was generally consistent with stakeholders' storage management objectives (GWMWater, 2014). This review made 40 recommendations to improve system operation which are summarised below. Note that the management objectives are in italics font and the number in brackets refers to the number of recommendations made with respect to that particular management objective:

- "*To direct operations to ensure that the structural and operational integrity of the Wimmera-Mallee system headworks is maintained*."
  Improve overall system efficiency by introducing a range of works (x2)
- "*To deliver water to entitlement holders in a timely, transparent and efficient manner*."
  Formalising existing arrangements in the delivery of environmental flows (x1)

- "*To account for the water stored and water flows in the Wimmera-Mallee system headworks and for the water taken by entitlement holders.*"

  Improving water accounting particularly for carryover (x6)
- "*To maintain and, when the need arises, to enhance, the security of supply to water entitlement holders with particular emphasis on contingency planning to avoid water shortages and measures to reduce water losses in the Wimmera-Mallee system headworks.*"

  Improving flexibility in water delivery by increasing the maximum operating volume from 75% to 85% full supply volume for Rocklands Reservoir (x6)
- "*To facilitate the transfer of water entitlements and allocations between entitlement holders.*"

  Educating water users of the benefits of water trade through the preparation of guidance papers (x1)
- "*To facilitate the implementation of environmental watering activities, including activities under the environmental operating plan.*"

  Developing more holistic management plans that improve watering arrangements between water agencies (x6)
- "*To facilitate the achievement of environmental outcomes, and mitigate significant environmental events, such as fish kills, unseasonal water, algal blooms, river bank erosion and acidification.*"

  Developing a collaborative approach to addressing water quality issues (x2)
- "*To manage water quality in the Wimmera-Mallee system headworks so that it is fit for purpose for urban, irrigation, industrial, stock and domestic, and environmental use.*"

  Improving water quality monitoring by expanding current arrangements to include other parts of the system (x1)
- "*To provide opportunities for recreation activities in the Wimmera-Mallee system headworks where that is compatible with other objectives.*"

  Improving the recreation amenity at sites in the system that have high social value by employing a range of works including increasing the recreation water entitlement (x10)
- "*To manage floods in the Wimmera-Mallee system headworks to conserve water and manage impacts on communities, including the supply of water to recreational lakes where this is compatible with the environmental objectives.*"

Improving the guidelines for storage operations during floods (x3)

- "*To facilitate the protection of Aboriginal cultural heritage, in accordance with relevant cultural heritage management plans and by other means.*"
  Improving involvement of indigenous groups in planning processes (x1)
- (Development of an implementation plan, which was not a specific management objective, was also recommended as part of the review project in order to assist with the delivery of the above recommendations, x2)

Based on the number of recommendations under each management objective, the social interests for water in terms of recreation amenity was one area that required a great deal of attention (i.e. 10 out of 40 recommendations). Another two areas requiring a higher level of attention which are particularly relevant to this study are the recommendations to develop more holistic management plans for improving environmental watering arrangements and the recommendations to increase the maximum operating volume at Rocklands Reservoir. The first and second of these recommendations, are directly related to the problem formulation phase which ought to explicitly account for all interests for water. The third of these recommendations is in contradiction to the results for the highest ranked SI operating plans found by the O-S model under each of the three hydro-climatic conditions considered in this thesis (refer to dv_{18} in Table 4.11). However as explained earlier, the formulation of the MOOPs using system-wide interests in terms of users' water allocations (instead of headworks loss) may not necessarily be able to guide the optimisation search towards more efficient modes of operation.

5.2.3 Conclusions

The purpose of Section 5.2 was to confirm the validity of the optimal operating plans found under historic hydro-climatic conditions in Chapter 4 (i.e. Run (A1)) against the optimal operating plans under the low to medium level GHG emission scenario (i.e. Run (A2)) and the medium to high level GHG emission scenario (i.e. Run (A3)). The outcomes of the analysis of the base case operating plan and the highest ranked SI operating plans found by the O-S model under each of the three hydro-climatic conditions are summarised as follows:

- The SI curves of the optimal operating plans under Run (A1) and Run (A3) showed that the base case operating plan was neither the highest nor the lowest in terms of the level of sustainability that could be achieved in the WGWSS (in terms of SI). Note that the dominance test for the base case operating plan against the optimal plans under Run (A2) confirmed that the base case operating plan was not optimal under low to medium GHG emissions. The highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3) were Plan no. 11 ($SI = 0.5$), Plan no. 49 ($SI = 0.66$), and Plan no. 46 ($SI = 0.53$) respectively.
- The dominance test and the SI were used to short list optimal operating plans that were considered robust (i.e. capable of withstanding the changed hydro-climatic conditions given by the GHG emissions under Run (A2) and Run (A3)). The dominance test results together with the SI values showed that the highest ranked SI operating plans were indeed robust whereas the base case operating plan was not robust given that it was not optimal under low to medium GHG emissions. However the simulation modelling outputs (in the form of a water balance) showed that the base case operating plan consistently provided (i) similar consumptive use volumes; (ii) the lowest volumes of headworks loss; and (iii) the highest total (regulated and unregulated) environmental flow volumes under the three hydro-climatic conditions.
- In general, the results for Plan no. 49 under Run (A2) and Plan no. 46 under Run (A3) showed a degree of inconsistency with the planning decisions for Plan no. 11 under Run (A1). This inconsistency suggested that consumptive users at Lake Wartook and/or Rocklands Reservoir would experience a greater impact than that under historic hydro-climatic conditions. These results together with the water balance results showed that (i) the apparent inconsistency was in fact an alternative set of optimal operating rules (to those under Plan no. 11) which favoured environmental interests for water over social and consumptive interests; and (ii) that the impact would be experienced by all consumptive users in the system and not localised around Lake Wartook and Rocklands Reservoir.
- The water balance results also showed that there would be a disproportionate impact between environmental flows and consumptive users under the highest ranked SI operating plans compared to that under the base case operating plan. The results for the highest ranked SI operating plans showed that there would

be a significant reduction in the total environmental flow (regulated) compared to a small change in the total consumptive use under each of the three hydro-climatic conditions.

- Plan no. 49 and Plan no. 46 had identical f values which meant that their CI values and SI values were identical under each of the three hydro-climatic conditions. The outcomes of the decision space analysis showed that the reason for the two plans achieving the same level of sustainability for the WGWSS was due to these plans sharing the same value for all but one of the decision variables. It was explained that the one exception was the planning decision representing the priority of supply between the consumptive demands from Rocklands Reservoir and the EWD in the Glenelg River (i.e. dv_5), and that its value was influenced by the availability of water in both the Glenelg River and Wimmera basin. On balance, the results showed that dv_5 was not sensitive to the decline in water availability caused by the GHG emissions.

The outcomes of a recent review of the operation of the WGWSS showed that the base case operating plan was generally consistent with stakeholders' storage management objectives. Of particular interest to this thesis was that the review made recommendations to improve the inclusion of social interests for water in terms of recreation amenity, to develop more holistic management plans for environmental watering purposes, and to increase the maximum operating volume at Rocklands Reservoir. The first and second of these recommendations are directly related to the problem formulation phase which ought to explicitly account for all interests for water. The third of these recommendations was in contradiction to the results for the highest ranked SI operating plans found by the O-S model under each of the three hydro-climatic conditions. However as explained earlier, the formulation of the MOOPs using system-wide interests in terms of users' water allocations (instead of headworks loss) may not necessarily be able to guide the optimisation search towards more efficient modes of operation. Moreover it was explained that the disproportionate impact borne by the regulated environmental flows would be an important consideration in Victoria (Australia) where such an in-balance could lead to a review of the management of water resources.

5.3 Selection of preferred optimal operating plan for the WGWSS

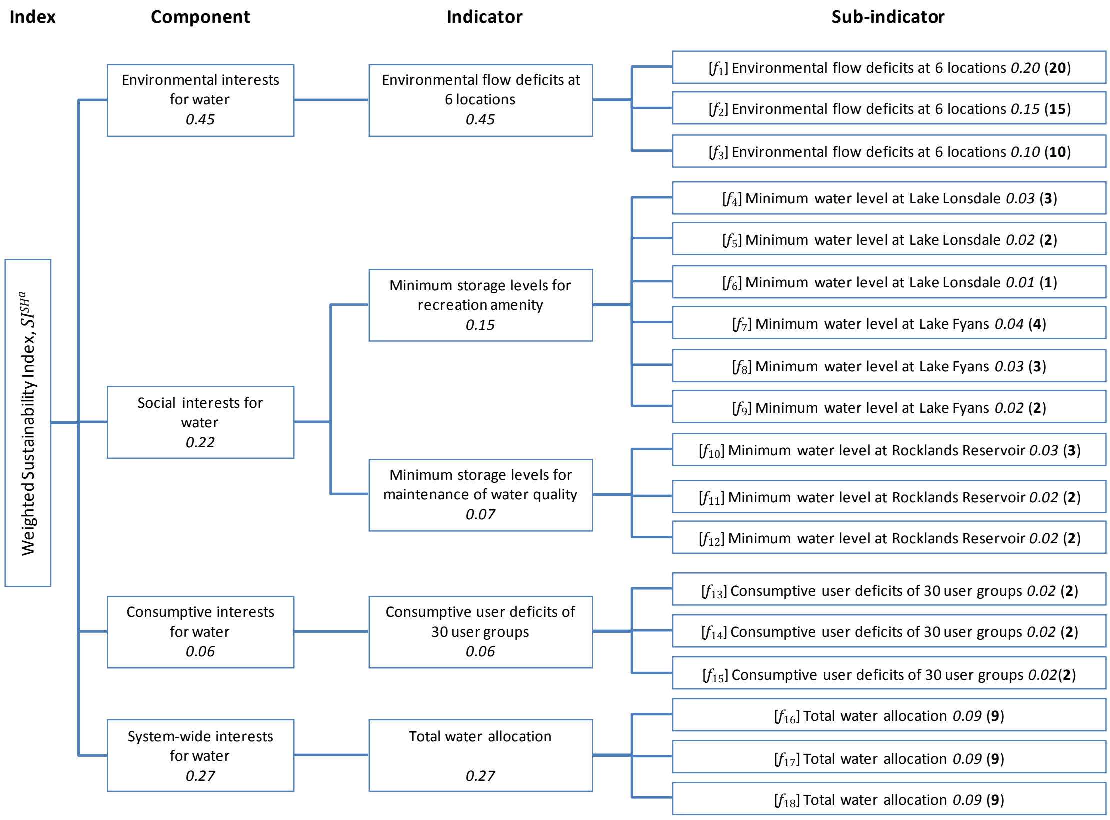
According to Deb (2001) the ideal multi-objective optimisation approach involves finding a diverse set of optimal solutions followed by the selection of a solution(s) using higher-level qualitative information. The first of these two areas of work were described in Chapter 3 to Chapter 5 (thus far). Chapter 3 presented a higher order MOOP for the WGWSS which was structured hierarchically in terms of a value tree. The top of the value tree represented the sustainability of the WGWSS corresponding to the SI for the WGWSS. The bottom of the value tree consisted of various conflicting criteria which corresponded to the 18 objective functions of the MOOP. Chapter 4 showed that this problem formulation could be used by the O-S model to find the Pareto front of optimal operating plans assuming historic hydro-climatic conditions. Section 5.2 tested the validity of the base case operating plan and the highest ranked SI operating plan (found under historic hydro-climatic conditions) assuming two plausible GHG emission scenarios. This testing process allowed for the short-listing of three robust optimal operating plans which were able to withstand all three hydro-climatic scenarios. The second of the two areas of work described above is the subject of this section which aims to incorporate stakeholders' preferences in the DM's selection of a preferred optimal operating plan.

5.3.1 Stakeholder preferences

Having completed the problem formulation phase and found the Pareto fronts under all three hydro-climatic conditions, it becomes necessary to develop a conceptual model which represents stakeholders' preferences and value judgements. Methods available under the umbrella term multi-criteria decision analysis (MCDA) are widely used for the purpose of facilitating the exploration of decisions that take explicit account of multiple factors or criteria (Belton and Stewart, 2002). As explained in Chapter 3, the use of the SI (in evaluating and comparing optimal operating plans) lends itself to the value measurement preference model. This is due to the SI providing (i) a means of associating a real number for each optimal operating plan; and (ii) an ordering or ranking of these plans, where SI values of 0 and 1 represent the lowest and highest levels of sustainability in the WGWSS respectively. The resulting j^{th} stakeholder's Weighted Sustainability Index, SI^j, is provided in Equation 5.10. Note that for ease of referencing the relevant objective function equation in Chapter 5, SI^j is expressed in terms of w_x^j (i.e. the j^{th} stakeholder's weight for the x^{th} objective function, f_x) instead of w_m^j (i.e. the j^{th} stakeholder's weight for the m^{th} performance metric).

For the purposes of demonstrating the application of the SI^j, three sets of preference vectors were gleaned from the available stakeholder information collected as part of recent water resource planning studies of the WGWSS (GWMWater, 2007; 2012a; 2012b; DSE, 2011). These stakeholder preferences are assumed to represent those stakeholders that have (i) higher environmental preferences relating to ecological health of waterways including the flora and fauna that depend on these natural ecosystems (SH^a); (ii) higher social preferences concerning water for recreation and for maintenance of water quality SH^b); and higher preferences for the needs of consumptive users such as for urban centres, irrigators, and other water-dependant industries (SH^c). Figure 5.3 to Figure 5.5 are diagrammatic representations of the value tree used in the formulation of the MOOP showing the preferences of the three stakeholders (i.e. SH^a, SH^b, and SH^c).

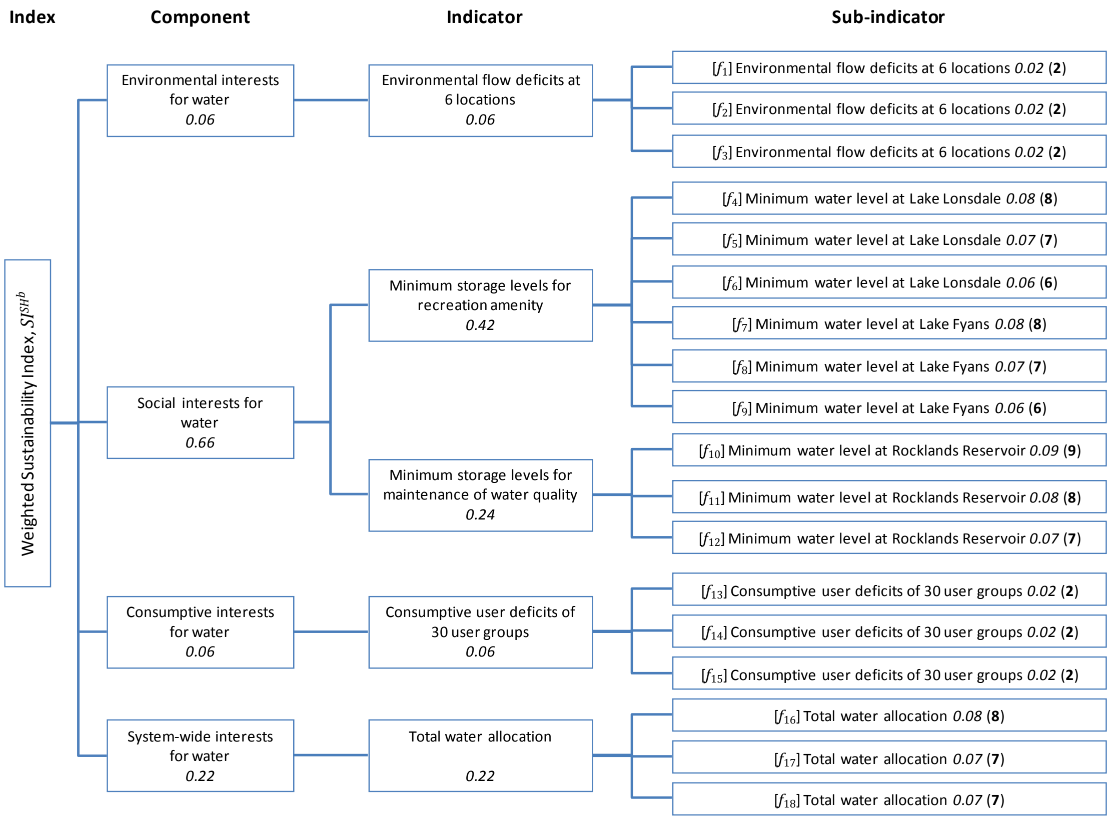
Note that for ease of presentation, the top of the tree is shown on the left of the figure and the bottom of the tree (i.e. the leaves) are on the right. Accordingly, the Weighted Sustainability Index representing environmental, social, and consumptive stakeholder preferences are denoted SI^{SH^a}, SI^{SH^b}, and SI^{SH^c} respectively.



Note: 'f_x' refers to objective function x as defined in Section 5.2.1.

Figure 5.3 Value tree of a higher MOOP of WGWSS showing preferences of SH^a in terms of cumulative weights (in italic font) and corresponding ratios (in bold font)

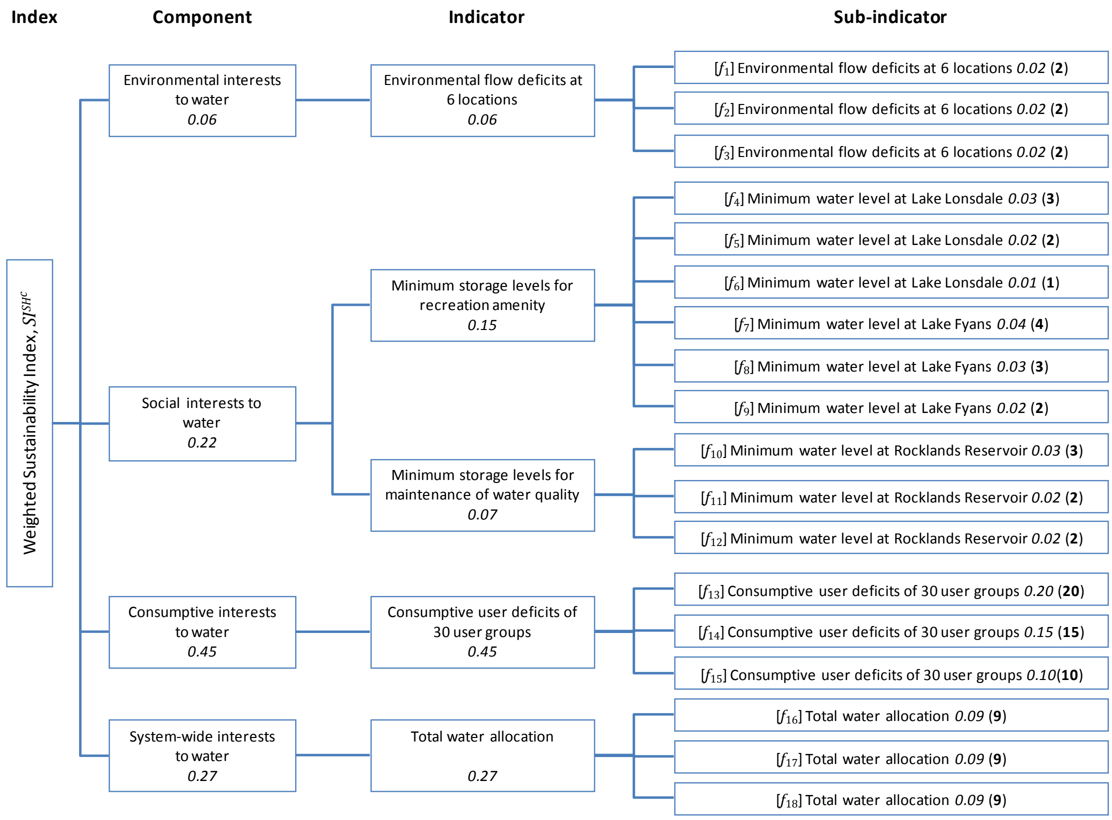
It is important to distinguish between the two forms of stakeholder preferences presented in Figure 5.3 to Figure 5.5 being cumulative weights in italic font and ratios in bold font. As the SI^j uses a ratio scale of preferences, the ratios are used for the bottom level of the value tree in the first instance. Note that the ratios are only shown for the bottom level of the value tree in Figure 5.3 to Figure 5.5 given that the SI^j will be computed from the corresponding 18 objective function values later in Section 5.3.2. The second step involved normalising these ratios to produce cumulative weights which allowed for higher levels of the value tree to be determined. Note that the cumulative weight of a parent criterion is the total of the cumulative weights of its descendants.



Note: 'f_x' refers to objective function x as defined in Section 5.2.1.

Figure 5.4 Value tree of a higher MOOP of WGWSS showing preferences of SH^b in terms of cumulative weights (in italic font) and corresponding ratios (in bold font)

Figure 5.3 shows that SH^a considers the preferences of environmental, social, consumptive, and system-wide interests for water to be in the ratio of 45:22:6:27 (i.e. (20+15+10):(3+2+1+4+3+2+3+2+2):(2+2+2):(9+9+9). Note that the highest preference for SH^{env} is attributed to the environmental interests for water (i.e. objective functions f_1 to f_3) which is consistent with the earlier assumption. Figure 5.4 shows that SH^b considers the preferences of environmental, social, consumptive, and system-wide interests for water to be in the ratio of 6:66:6:22. Figure 5.5 shows that SH^c has the same preferences as SH^a except for the environmental interests for water and the consumptive interests which are reversed (i.e. 6:22:45:27).



Note: 'f_x' refers to objective function x as defined in Section 5.2.1.

Figure 5.5 Value tree of a higher MOOP of WGWSS showing preferences of SH^c in terms of cumulative weights (in italic font) and corresponding ratios (in bold font)

5.3.2 Post-processing results and discussion

5.3.2.1 <u>Objective space</u>

This section uses the results from O-S modelling runs presented in Section 4.4 and Section 5.2 to calculate CI_i^j and SI^j for the j^{th} stakeholder (i.e. SH^a, SH^b, and SH^c) with respect to the i^{th} interest for water (i.e. environmental, social, consumptive, and system-wide interests). The mathematical formulae for CI_i^j are given in Equations 5.6 to 5.9 and the SI^j is given in Equation 5.10.

Table 5.12 summarises the three sets of CI and SI values for the robust optimal operating plans (i.e. Plan no. 11, Plan no. 49, and Plan no. 46) with respect to each of SH^a, SH^b, and SH^c. The first two columns under each of the three hydro-climatic scenarios present these values without applying the stakeholder preferences. Note that these values are the same as those presented earlier in Table 5.4. The third and fourth columns under each of the three hydro-climatic scenarios present the CI_i^j and SI^j with stakeholder preferences SH^a, SH^b, and SH^c applied to them as specified in Equations 5.6 to 5.10. Note that Plan no. 49 and Plan no. 46 are combined in a single column in each case as the results in Section 5.2 showed that the WGWSS performed exactly the same under the two operating plans. The shaded results in Table 5.12 represent the best outcome (i.e. the highest values) between corresponding (non-weighted and weighted) CI and SI values. The shading of the best outcome in each case is colour-coded to align with the same hydro-climatic conditions (i.e. light/dark grey shade - historic hydro-climatic conditions, light/dark red shade - low to medium level GHG emissions, and light/dark green shade – medium to high level GHG emissions). Note that for consistency, the values which do not have the stakeholder preferences applied to them are the same light-coloured shade used in Table 5.3 and Table 5.4.

Table 5.12 shows that the relativity between Plan no. 11 and Plan no. 49/Plan no. 46 in terms of any corresponding CI_i and CI_i^j values is the same under each of the three hydro-climatic conditions, regardless of the stakeholder preference applied. For example, under the low to medium hydro-climatic conditions, the CI_{env} value of Plan no. 11 is less than Plan no. 49/Plan no. 46 (i.e. $0.28 < 0.32$) and the same occurs in the $CI_{env}^{SH^a}$ (i.e. $0.22 < 0.27$). Note that whilst the CI_i and CI_i^j relativities are the same, their absolute values can change subject to the stakeholder preferences and, depending on the product of these changed values, may cause SI^j to change relative to SI. Using the same example, the stakeholder preferences SH^a caused a change in the values for $CI_{env}^{SH^a}$, $CI_{socio}^{SH^a}$, and $CI_{cons}^{SH^a}$ changing the relativity between the SI^{SH^a} values for Plan no. 11 and Plan no. 49/Plan no. 46 compared to the corresponding SI values (i.e. $SI: 0.74 > 0.66$ c.f. $SI^{SH^a}: 0.49 < 0.51$). Note that this same effect occurs three times and is circled in red. This also means that with the exception of these three instances, the stakeholder preferences did not change the relativities between SI and SI^j.

Table 5.12 Values of Component-level Index and Sustainability Index (without and with stakeholder preferences) for the shortlisted robust optimal operating plans under historic hydro-climatic conditions and two GHG emission scenarios

Component-level Index (CI_i) and Sustainability Index (SI)	Description	CI_i (italic font) and SI (bold italic font)												
		Ratio preference for the j^{th} stakeholder (SH^j)	Historic hydro-climatic conditions				Low to medium GHG emissions				Medium to high GHG emissions			
			Run (A1) - Plan no. 11	Plan no. 49* & Plan no. 46*	Run (A1) - Plan no. 11	Plan no. 49* & Plan no. 46*	Plan no. 11*	Run (A2) - Plan no. 49 & Plan no. 46*	Plan no. 11*	Run (A2) - Plan no. 49 & Plan no. 46*	Plan no. 11*	Plan no. 49* & Run (A3) - Plan no. 46	Plan no. 11*	Plan no. 49* & Run (A3) - Plan no. 46
Environmental stakeholder preferences:		SH^a	Values without SH^a		Values with SH^a		Values without SH^a		Values with SH^a		Values without SH^a		Values with SH^a	
CI_{env}	*Environmental Component-level Index - Equations (5.1) & (5.6)*	*45*	*0.52*	*0.61*	*0.47*	*0.58*	*0.28*	*0.32*	*0.22*	*0.27*	*0.22*	*0.32*	*0.17*	*0.26*
CI_{socio}	*Social Component-level Index - Equations (5.2) & (5.7)*	*22*	*0.43*	*0.48*	*0.50*	*0.55*	*0.92*	*0.83*	*0.94*	*0.86*	*0.64*	*0.56*	*0.69*	*0.61*
CI_{cons}	*Consumptive Component-level Index - Equations (5.3) & (5.8)*	*6*	*0.70*	*0.54*	*0.66*	*0.47*	*0.74*	*0.47*	*0.69*	*0.40*	*0.48*	*0.39*	*0.42*	*0.32*
CI_{sys}	*System-wide Component-level Index - Equations (5.4) & (5.9)*	*27*	*0.52*	*0.53*	*0.52*	*0.53*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
SI	*Sustainability Index - Equations (5.5) & (5.10)*	***na***	***0.50***	***0.52***	***0.50***	***0.55***	***0.74***	***0.66***	***0.49***	***0.51***	***0.55***	***0.53***	***0.40***	***0.46***
Social stakeholder preferences:		SH^b	Values without SH^b		Values with SH^b		Values without SH^b		Values with SH^b		Values without SH^b		Values with SH^b	
CI_{env}	*Environmental Component-level Index - Equations (5.1) & (5.6)*	*6*	*0.52*	*0.61*	*0.45*	*0.56*	*0.28*	*0.32*	*0.20*	*0.25*	*0.22*	*0.32*	*0.15*	*0.24*
CI_{socio}	*Social Component-level Index - Equations (5.2) & (5.7)*	*66*	*0.43*	*0.48*	*0.43*	*0.48*	*0.92*	*0.83*	*0.93*	*0.84*	*0.64*	*0.56*	*0.63*	*0.55*
CI_{cons}	*Consumptive Component-level Index - Equations (5.3) & (5.8)*	*6*	*0.70*	*0.54*	*0.66*	*0.47*	*0.74*	*0.47*	*0.69*	*0.40*	*0.48*	*0.39*	*0.42*	*0.32*
CI_{sys}	*System-wide Component-level Index - Equations (5.4) & (5.9)*	*22*	*0.52*	*0.53*	*0.53*	*0.54*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
SI	*Sustainability Index - Equations (5.5) & (5.10)*	***na***	***0.50***	***0.52***	***0.46***	***0.50***	***0.74***	***0.66***	***0.84***	***0.77***	***0.55***	***0.53***	***0.63***	***0.58***
Consumptive stakeholder preferences:		SH^c	Values without SH^c		Values with SH^c		Values without SH^c		Values with SH^c		Values without SH^c		Values with SH^c	
CI_{env}	*Environmental Component-level Index - Equations (5.1) & (5.6)*	*6*	*0.52*	*0.61*	*0.45*	*0.56*	*0.28*	*0.32*	*0.20*	*0.25*	*0.22*	*0.32*	*0.15*	*0.24*
CI_{socio}	*Social Component-level Index - Equations (5.2) & (5.7)*	*22*	*0.43*	*0.48*	*0.50*	*0.55*	*0.92*	*0.83*	*0.94*	*0.86*	*0.64*	*0.56*	*0.69*	*0.61*
CI_{cons}	*Consumptive Component-level Index - Equations (5.3) & (5.8)*	*45*	*0.70*	*0.54*	*0.67*	*0.49*	*0.74*	*0.47*	*0.71*	*0.43*	*0.48*	*0.39*	*0.44*	*0.35*
CI_{sys}	*System-wide Component-level Index - Equations (5.4) & (5.9)*	*27*	*0.52*	*0.53*	*0.52*	*0.53*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
SI	*Sustainability Index - Equations (5.5) & (5.10)*	***na***	***0.50***	***0.52***	***0.57***	***0.52***	***0.74***	***0.66***	***0.77***	***0.61***	***0.55***	***0.53***	***0.57***	***0.51***

'CI_i' refers to the Component-level Index for the i^{th} interest for water as defined in Section 5.1. Refer to Equations 5.6 to 5.9 for the Weighted Component-level Index.
'SI' refers to the Sustainability Index for the Wimmera-Glenelg Water Supply System as defined in Equation 5.5. Refer to Equation 5.10 for the Weighted Sustainability Index.
* refers to operating plans that have been modelled under the given hydro-climatic conditions using simulation-only as distinct to plans that have been found by optimisation-simulation modelling.
'na' means not applicable.

Overall the SI and SI^j results show that there is consensus that Plan no. 49/Plan no. 46 is the most preferred under historic hydro-climatic conditions and that Plan no. 11 is most preferred under the GHG emission scenarios.

5.3.2.2 Decision space

Section 5.2.2.2 presented a detailed analysis of the decision variable values for each of the 24 planning decisions under Plan no. 11, Plan no. 49 and Plan no. 46. The analysis (alone) showed that there was a degree of inconsistency with the planning decisions under Plan no. 49 and Plan no. 46 compared to those under Plan no. 11. However with the aid of a system water balance (refer to Section 5.2.2.3), the apparent inconsistency in Plan no. 49 and Plan no. 46 was shown to be an alternative set of optimal operating rules to those under Plan no. 11 which simply favoured environmental interests for water over social and consumptive interests. This explains in part the results in Table 5.12, in so far as the change in the relativity between the SI^j values for Plan no. 11 and Plan no. 49/Plan no. 46 compared to the corresponding SI values. That is, a stakeholder who has high environmental preferences such as SH^a will accentuate this preference in the SI^{SH^a} value for optimal plans like Plan no. 49 and Plan no. 46 which already favour environmental interests for water. Similarly, a stakeholder who has high consumptive preferences such as SH^c will accentuate this preference in the SI^{SH^c} value for optimal plans like Plan no. 11 which already favour consumptive interests for water. On this basis, the reason that the preferences for SH^b do not change from one plan to another is that the environmental and consumptive preferences are the same. This means that the higher social preferences of SH^b (alone) are not enough to change the preference for one plan over another for this stakeholder. However, what is not known from this analysis is the preference ratio which causes this reversal in relativities of SI and SI^j values. The answer to this question requires further investigation and discussion as provided in Section 5.3.2.3.

5.3.2.3 Discussion

The results of the objective space analysis (i.e. Section 5.3.2.1) showed how the SI^j could be used to select a preferred optimal operating plan by incorporating stakeholder preferences in the SI. However Belton and Stewart (2002) point out that the determination of an overall value (in a value measurement preference model) should not be viewed as the end of the analysis. The authors explain that the value (i.e. the

SI^j in this case) ought to be considered as another step in furthering the understanding and promoting discussion about the problem. Indeed, the SI^j like the SI is by definition an indicator of the level of sustainability that can be achieved in the WGWSS under a given optimal operating plan. The DM needs to be aware that further exploration is required in terms of the composition of the optimal operating plan (i.e. decision space) and in terms of the performance of the WGWSS beyond that provided by the performance metrics alone (i.e. simulation modelling). Similarly, exploration of alternative perspectives of the problem can be undertaken in terms of a sensitivity analysis in order to explore (among other areas) the effect of the stakeholder's uncertainty about their values and priorities or simply to offer a different perspective on the problem.

Belton and Stewart (2002) view this sensitivity analysis from a technical, individual, and a group perspective. The author's describe the technical sensitivity analysis as one that examines the effect of changes to the input parameters of the model on the output of a model. In this way, the analysis sets out to determine the level of influence that the various input parameters have on the overall evaluation (i.e. the SI^j in this case). The individual's perspective is to provide a sounding board against which a stakeholder can test their intuition and understanding of the problem. The group perspective often involves the exploration of alternative perspectives, which Belton and Stewart (2002) explain, is often undertaken by using different sets of criteria weights as was presented in Section 5.3.2.1. Given that the source of stakeholder preference information was from a desktop study rather than the elicitation of actual preferences, the individual perspective can be ruled out in so far as this thesis is concerned. For this reason, the sensitivity analysis presented in this section is viewed from a technical perspective which examines the effect of changes to input parameters of the SI^j.

From the outcomes of the objective space analysis in Section 5.3.2.1, the obvious input parameters to be examined are the SH^a and SH^b stakeholder preferences which were shown to cause a change in the overall preferred optimal operating plan in terms of SI and SI^j. The results in Table 5.12 showed that the preferred plan of SH^a changed from Plan no. 11 in terms of SI to Plan no. 49/Plan no. 46 in terms of SI^{SH^a} under the two GHG emissions scenarios. This meant that the change in stakeholder preferences, from equal preferences to those given by SH^a (i.e. from 1:3:1:1 to 45:22:5:27), caused SH^a to change its preference in terms of which optimal plan it considered the most preferable under the two GHG emission scenarios. Similarly the results in Table 5.12 showed that the preferred plan of SH^c changed from Plan no. 49/Plan no. 46 in terms of SI to Plan no. 11 in terms of SI^{SH^c} under historic hydro-climatic conditions. This meant that the change in stakeholder preferences, from equal preferences to those given by SH^c (i.e. from 1:3:1:1 to 5:22:45:27), caused SH^c to change its preference in terms of which optimal plan it considered the most preferable under historic hydro-climatic conditions. Hence, the difference in the preference ratios of SH^a and SH^c are in terms of environmental and consumptive interests only, with the preferences of social and system-wide interests for water being equal.

For brevity, the sensitivity of changes in the preference ratios of SH^a are examined which provides the basis for examining the preference ratios of other stakeholders, as required. Figure 5.6 shows the effect of changes to the preference ratios of SH^a for the three optimal operating plans under all three hydro-climatic conditions.

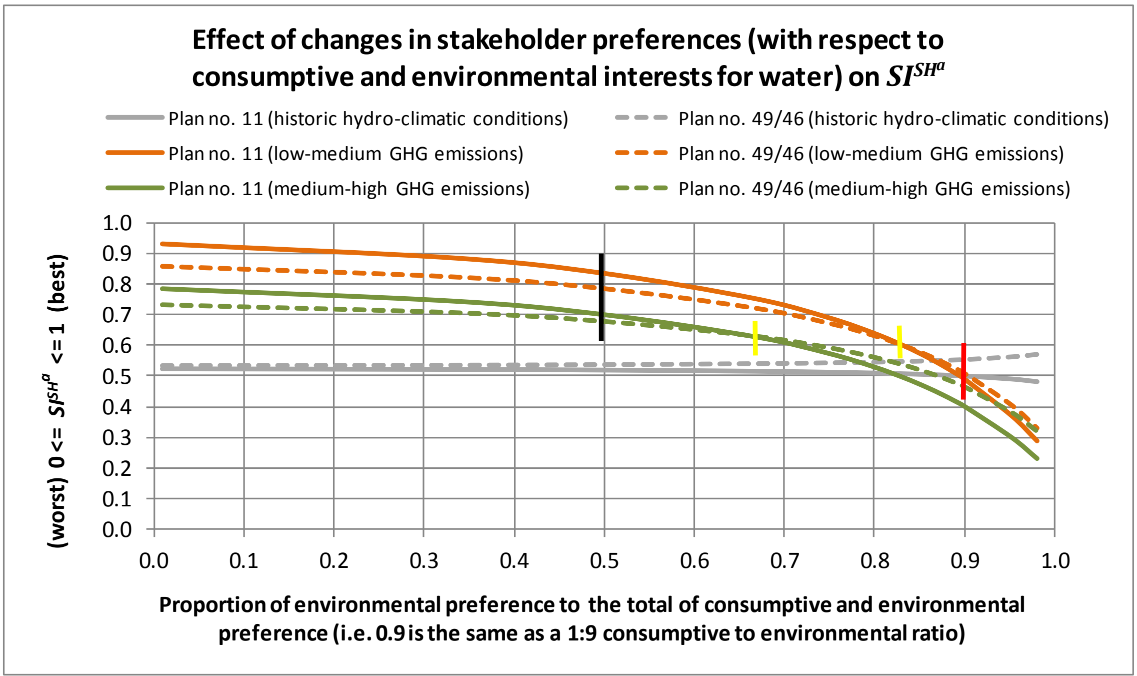


Figure 5.6 Effect of changes in stakeholder preferences (with respect to consumptive and environmental interests for water) on SI^{SH^a}

The vertical axis of the figure shows the corresponding SI^{SH^a} value for different ratios of consumptive to environmental preferences. The horizontal axis shows the range of consumptive:environmental preference ratios on a linear scale so that a ratio of 1:1 is equal to the proportion of the environmental preference to the total of consumptive and environmental preferences (i.e. $\frac{1}{1+1} = 0.5$), referred to here as the *proportional preference*. Note that for convenience and ease of reference, the colours of the three sets of curves align with those presented in Table 5.4 and Table 5.12.

The three sets of curves presented in Figure 5.6 confirm the changes observed in the preferences of SH^a as described earlier. For instance, the curves for Plan no. 11 and Plan no. 49/46 under low to medium GHG emissions show that the SI^{SH^a} value for Plan no. 11 is higher than that for Plan no. 49/46 (as intersected by the thick black vertical line at the proportional preference of 0.5). However at the proportional preference of 0.9 which corresponds to the preference of SH^a (as intersected by the thick red vertical line), the SI^{SH^a} value for Plan no. 11 is lower than that for Plan no. 49/46. Similarly, the same reversal in SI^{SH^a} values occurs for the optimal plans under medium to high GHG emissions. Importantly, the difference in the two sets of curves is that the reversal or turning points occur at different preference ratios (as intersected by the thick yellow vertical lines). Under the low to medium GHG emissions, the turning point occurs at a proportional preference of 0.83 (or a ratio of 1:5) where as under the medium to high GHG emissions, the turning point occurs at a proportional preference of 0.67 (or a ratio of 1:2). This informs the DM of the effort that should be placed on clarifying or confirming a stakeholder's uncertainty about their values and priorities. For instance, a higher level of effort would be placed on ascertaining stakeholders' preferences in a situation where stakeholders were indecisive between a proportional preference of 0.8 and 0.9 under the low to medium GHG emissions (i.e. ratios of 1:4 and 1:9).

Another important observation is made with respect to the three sets of curves shown in Figure 5.6. For each optimal plan, the rate of change in that plan's $SI^{SH^a}$is different under the three hydro-climatic conditions. Whilst the two sets of curves for the GHG emission scenarios are similar, the rate of change in $SI^{SH^a}$for the two plans under historic hydro-climatic conditions exhibit a marked reduction in the rate of change and also a turning point at a near-zero proportional preference (or a ratio of 1:100). This means that the preferences of SH^a with respect to consumptive interests would have to be virtually non-existent relative to its preference for environmental interests for water. In this case, such sensitivity analysis increases the DM's understanding of the way in which stakeholders' preferences affect the SI^{SH^a}under a range of hydro-climatic conditions.

5.3.3 Conclusions

The purpose of Section 5.3 was to incorporate stakeholders' preferences in the DM's selection of a preferred optimal operating plan. For this purpose, the j^{th} stakeholder's Weighted Sustainability Index, SI^j, was used to evaluate and compare the three robust optimal operating plans (i.e. Plan no. 11, Plan no. 49, and Plan no. 46) with respect to three sets of stakeholder preferences gleaned from real-world planning studies in the WGWSS. These stakeholder preferences represented those stakeholders that have higher environmental preferences (SH^a); higher social preferences concerning water for recreation and for maintenance of water quality (SH^b); and higher preferences for the needs of consumptive users (SH^c). Specifically, the outcomes of this section may be summarised as follows:

- The SI^j provided a simple means to incorporate stakeholders' preferences and served as a useful tool to evaluate and compare optimal operating plans.
- The objective space analysis showed that the relativity between Plan no. 11 and Plan no. 49/Plan no. 46 in terms of any corresponding CI_i and CI_i^j values was the same under each of the three hydro-climatic conditions, regardless of the stakeholder preference applied. For instance, under the low to medium hydro-climatic conditions, the CI_{env} value of Plan no. 11 was less than Plan no. 49/Plan no. 46 (i.e. $0.28 < 0.32$) and the same occurred in the $CI_{env}^{SH^a}$ (i.e. $0.22 < 0.27$). It was explained that whilst the CI_i and CI_i^j relativities were the same, their absolute values could change subject to the stakeholder preferences and that depending on the product of these changed values, could cause SI^j to change relative to SI. This reversal in relativities of SI and SI^j values which is discussed further in the next point was shown to occur three times. Overall the SI and SI^j results showed that there was consensus for accepting Plan no. 49/Plan no. 46 under historic hydro-climatic conditions and that Plan no. 11 would be the most preferred under the GHG emission scenarios.

- The decision space analysis referred to the outcomes of previous work in this thesis which showed that the planning decisions made under Plan no. 49 and Plan no. 46 were simply an alternative set of optimal operating rules to those under Plan no. 11 which favoured environmental interests for water over social and consumptive interests. Moreover, the analysis showed that a stakeholder who had high environmental preferences such as in SH^a, would accentuate this preference in its SI^{SH^a} value for optimal plans (like Plan no. 49 and Plan no. 46) which already favoured environmental interests for water. Similarly, it was shown that a stakeholder who had high consumptive preferences such as SH^c, would accentuate this preference in its SI^{SH^c} value for optimal plans (like Plan no. 11) which already favoured consumptive interests for water. On this basis, it was explained that the reason for no change in preference between the optimal plans with respect to SH^b was due to the environmental and consumptive preferences being the same for this stakeholder. This meant that the higher social preferences of SH^b (alone) were not enough to change the preference for one plan over another for this stakeholder.

Furthermore, a sensitivity analysis of the effect of changing the consumptive:environmental preference ratio on the SI^{SH^a} value for the three robust optimal operating plans was presented and discussed. The results of this analysis confirmed the findings made as part of the objective space analysis and decision space analysis as summarised above. Importantly it showed that such analysis would (i) inform the DM of the effort that ought to be placed on confirming a stakeholder's uncertainty about their values/priorities; and (ii) increase the DM's understanding of the way in which stakeholders' preferences affected the SI^{SH^a}under a range of hydro-climatic conditions.

5.4 Summary

Chapter 5 applied the analytical approach presented and applied in Chapter 4 to MOOPs considering two plausible future GHG emission scenarios. The aims of the work in this chapter were to (i) evaluate and compare the optimal operating plans under historic hydro-climatic conditions against the optimal operating plans under these GHG emission scenarios; and (ii) select the most preferred optimal operating plan(s) by taking into account stakeholders' preferences. This involved the formulation of two

MOOPs for the WGWSS which were solved using the O-S modelling approach described in Chapter 3.

Section 5.2 presented two higher order MOOPs for the purposes of confirming the validity of the optimal operating plans found under historic hydro-climatic conditions, referred to as Run (A1). These two MOOPs were formulated in the same way with the only exception being that they assumed a different but plausible GHG emission level into the future, viz. low to medium (i.e. Run (A2)) and medium to high (i.e. Run (A3)) levels of GHG emissions. The analysis of the O-S modelling results showed that the highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3) were Plan no. 11 ($SI = 0.5$), Plan no. 49 ($SI = 0.66$), and Plan no. 46 ($SI = 0.53$) respectively. The dominance test and the SI were used to short list (robust) optimal operating plans from the Pareto fronts of each of the three runs. The three highest ranked SI operating plans were shown to be capable of withstanding the three hydro-climatic conditions. Interestingly, whilst the dominance test proved the base case operating plan was not optimal under low to medium GHG emissions, simulation modelling outputs showed that it consistently provided (i) similar consumptive use volumes; (ii) the lowest volumes of headworks loss; and (iii) the highest total (regulated and unregulated) environmental flow volumes under the three hydro-climatic conditions. An investigation into the composition of the SI, revealed that formulating the MOOP using system-wide interests in terms of users' water allocations (instead of headworks loss) would not have necessarily guided the optimisation search towards more efficient modes of operation. This highlighted the importance of explicitly accounting for headworks loss as part of the problem formulation phase.

Another key finding of Section 5.2 was in regards to what seemed to be an inconsistency in the operating rules between Plan no. 49 and Plan no. 46 compared to those under Plan no. 11. The results of the decision space analysis together with a system water balance revealed that the apparent inconsistency in Plan no. 49 and Plan no. 46 was simply an alternative set of optimal operating rules to those under Plan no. 11 which favoured environmental interests for water over social and consumptive interests. Moreover, the results of Section 5.2 were compared to the outcomes of a recent review of the operation of the WGWSS and also discussed in terms of the sharing of impacts amongst users under the GHG emission scenarios. The key finding of the review process was that the base case operating plan was generally consistent with stakeholders' storage management objectives. Of particular interest to this thesis, was that one of the major recommendations made by the review process was to increase the maximum operating volume at Rocklands Reservoir, which happened to be in contradiction to the results for the highest ranked SI operating plans found by the O-S model under each of the three hydro-climatic conditions. However as explained earlier, the formulation of the MOOPs in terms of users' water allocations would not have necessarily guided the optimisation search towards more efficient modes of operation. The discussion regarding the sharing of impacts focused on the disproportionality of this impact that was borne by the environment (compared to consumptive use) under the GHG emission scenarios. It was speculated that this would be an important consideration in Victoria (Australia) where such an in-balance could lead to a review of the management of water resources.

Section 5.3 applied the SI^j to the three *robust* optimal operating plans shortlisted earlier (in Section 5.2) for the purposes of selecting the most preferred optimal operating plan, considering all three hydro-climatic conditions. For this purpose, it was assumed that the DM considered three preference vectors representing those stakeholders that had higher environmental preferences (SH^a); higher social preferences concerning water for recreation and for maintenance of water quality (SH^b); and higher preferences for the needs of consumptive users (SH^c). A key finding of the analysis of the O-S modelling results showed that the SI^j provided a simple means to incorporate stakeholders' preferences and that it served as a useful tool to evaluate and compare optimal operating plans. Specifically, the objective space analysis showed that there was consensus for accepting Plan no. 49/Plan no. 46 under historic hydro-climatic conditions and that Plan no. 11 would be the most preferred under the GHG emission scenarios. The decision space analysis showed that a stakeholder who had high environmental preferences, such as in SH^a, would accentuate this preference in its SI^{SH^a} value for optimal plans (like Plan no. 49 and Plan no. 46) which already favoured environmental interests for water. Similarly, it was shown that a stakeholder who had high consumptive preferences, such as SH^c, would accentuate this preference in its SI^{SH^c} value for optimal plans (like Plan no. 11) which already favoured consumptive interests for water. Moreover, a sensitivity analysis of the effect of changing the consumptive:environmental preference ratio on the SI^j for the three robust optimal operating plans was presented and discussed. The results of the sensitivity analysis highlighted the importance of the SI^j in terms of (i) informing the DM of the effort that ought to be placed on confirming a stakeholder's uncertainty about their values/priorities; and (ii) increasing the DM's understanding of the way in which stakeholders' preferences affected the SI^j under a range of hydro-climatic conditions.

Chapter 6. Summary, conclusions and recommendations

6.1 Summary

This section provides a summary of the thesis in terms of the three phases of the proposed multi-objective optimisation procedure viz. (Phase 1) formulation of multi-objective optimisation problem (MOOP); (Phase 2) development of optimisation-simulation (O-S) model; and (Phase 3) selection of preferred Pareto-optimal solution(s). The three phases are consistent with the ideal multi-objective optimisation procedure proposed by Deb (2001). Firstly, the O-S model is used to provide the quantitative information in terms of the Pareto-optimal solutions, followed by the selection of preferred optimal operating plan(s) using qualitative information in terms of stakeholder preferences. This procedure was tested through the preparation of optimal operating plans for a case study of the Wimmera-Glenelg Water Supply System (WGWSS), assuming a range of hydro-climatic conditions. The WGWSS is located in north-western Victoria in Australia and is a multi-purpose, multi-reservoir system which is operated as a single water resources system; with many possible combinations of operating rules.

There are two major innovations of this research, viz; (i) the structured multi-objective optimisation procedure; and (ii) the analytical approach for evaluation of candidate optimal operating plans. The novelty in the structured multi-objective optimisation procedure is that it assists the DM to develop a shared vision for the operation of complex water resource systems by incorporating a greater level of realism into the decision-making process. The structured multi-objective optimisation procedure achieves this greater level of realism through, both, a holistic approach of formulating the problem and the use of O-S modelling. The problem formulation approach sets out a flexible basis on which to establish an overall goal for the water resources system and to set out the underlying individual goals of the various interests for water. The O-S modelling approach allows for the incorporation of complex operating rules and the latest advances in future climate projections through the use of trusted simulation model. Additionally, the optimisation model that is linked to this simulation model provides an efficient and effective means to conduct a far reaching or *global* search for candidate optimal operating plans. The novelty in the analytical approach which has been developed to evaluate candidate optimal operating plans is that it provides a visual means to communicate O-S modelling results for higher order MOOPs, in both the objective space and decision space. Importantly, this Sustainability Index (SI) is capable of quantifying sustainability by combining various performance metrics to represent the reliability, resiliency, and vulnerability of water resources systems over time. These two major innovations combine the formation of Pareto fronts for a range of hydro-climatic conditions with sustainability principles to deliver a practical tool that can be used to evaluate and select preferred Pareto-optimal solutions of higher order MOOPs for any water resources system. Such innovations have the potential to set a new precedent in the way operating plans are developed and reviewed over time.

The research methodology was influenced by a number of important factors which are directly related to solving higher order MOOPs, viz; the slow convergence of solutions to the Pareto front; and the high computational costs required to progress this search, particularly in the absence of parallel computing. Research has shown that the proportion of non-dominated solutions to the population size becomes very large as the number of objectives increases (Fleming et al., 2005; Deb, 2011). With respect to a population-based optimisation search, this increase in objectives has the effect of slowing the progression (i.e. *convergence*) of the population of solutions to the Pareto front. This slow convergence is largely attributed to a procedure (referred to in this thesis as the “dominance test”) which is applied to the solutions of the population in order to determine their non-dominance classification with respect to other solutions of the population. The slow convergence means that a greater number of O-S modelling generations are required to progress the solutions towards the Pareto front. The term *generation* refers to a (single) iteration of the O-S model. An increase in the number of generations requires greater computational processing effort, which in the case of population-based optimisation searches can be addressed through distributed or shared memory parallel computing architectures. However, such parallel computing capabilities were not available for this study, which meant that simulation runs for all solutions of the population had to be completed in series (i.e. one run at a time) before the optimisation search could be executed. For these reasons (of slow convergence and high computational costs), the number of generations performed by the O-S model was limited to five in number (throughout this thesis). Importantly, this is not to be confused as a research limitation given that the novelty of this study is that of the structured multi-objective optimisation procedure rather than finding Pareto fronts *per se*.

6.1.1 Formulation of MOOP

Phase (1) of the proposed multi-objective optimisation procedure involved the formulation of a higher order MOOP for the WGWSS which can be summarised in terms of five steps and structured as follows:

- Step (a) Identification of all the major interests for water i.e. the basis of the conflicting objectives to the optimisation problem;
- Step (b) Specification of the metrics that are used to evaluate the performance of the system in terms of its sustainability over a long term planning period;
- Step (c) Specification of the objective functions that are used by the O-S model to guide the search towards the Pareto front. It is important that the objective functions are developed based on Steps (a) and (b) in order to explicitly account for all the major interests for water identified;
- Step (d) Specification of the decision variables that control the operation of the system; and
- Step (e) Specification of the constraints that represent the variable limits of the MOOP and the physical characteristics of the system such as the capacity of storages, channels and pipes.

The following paragraphs expand on each of the above steps.

Four major interests for water were identified in the WGWSS viz. environmental, social (i.e. in terms of recreation and water quality), consumptive, and those that affected all users system-wide. As part of this identification process, relevant criteria by which to evaluate candidate optimal operating plans were also identified together with the various interests for water. For environmental interests for water the criteria adopted was the environmental flow deficit which was described as the difference between the amount that was required at a particular location (i.e. demand) and the amount that was provided to that location (i.e. supply). The criteria for social interests for water were described in terms of the volume held in storage for the provision for recreation amenity at two reservoirs and for the maintenance of water quality at another reservoir. As for environmental interests, the criteria for consumptive interests for water were described in terms of consumptive user deficits. The criteria for system-wide interests for water were described in terms of total system water allocations. The identification of these major interests for water was used as the basis for the higher order MOOP developed for this thesis.

For the above criteria to be incorporated in the higher order MOOP, suitable units of measure were developed to evaluate candidate optimal operating plans on a quantitative basis with respect to each of the interests for water identified. Three main performance metrics were used to evaluate the performance of the system in terms of its sustainability over a long term planning period viz. reliability, resiliency, and vulnerability. Reliability was defined as the frequency of desirable or successful events, resiliency referred to the rate of recovery of the water resources system after undesirable events or failures occur, and vulnerability was used to describe the severity of failures. For instance, in the case environmental interests for water the three main performance metrics were used to describe the reliability, resiliency, and vulnerability of environmental flow deficits. Therefore, a total of 18 performance metrics were developed from the three main performance metrics, being three for environmental interests; nine for social interests (i.e. for three different storages); three for consumptive interests; and three for all users system-wide. Importantly, these performance metrics summarised essential performance parameters in a meaningful manner which would assist the decision maker (DM) communicate with stakeholders as part of a decision-making process.

The specification of the 18 objective functions that were used as the basis of the higher order MOOP were directly linked to the interests for water via the 18 performance metrics. This was achieved using a hierarchical structure for which the sustainability of the WGWSS was assumed to represent the highest level criteria. The second level of the problem hierarchy represented the four major interests for water (i.e. environmental, social, consumptive, and system-wide interests) and the lowest level criteria represented the 18 objective functions for the MOOP. Structuring the higher order MOOP in this way provided the necessary means for taking into explicit account all the major interests for water in the WGWSS; and for the evaluation of candidate optimal operating plans. For instance, in the case of environmental interests for water, candidate optimal operating plans were evaluated in terms of maximising the reliability, maximising the resiliency, and minimising the vulnerability of environmental flow deficits. Therefore, the sustainability of the WGWSS was defined as the aggregation of the individual criteria for each of the environmental, social, consumptive, and system-wide interests for water. Importantly, such hierarchical structure highlights that formulating a MOOP using higher criteria levels (e.g. the four major interests for water) has the effect of reducing the dimensionality of the problem whereas lower criteria levels (e.g. the 18 objective functions) has the reverse effect.

The decision variables for the higher order MOOP were expressed in terms of 24 water management planning decisions representing the key operating rules which control and regulate the water resources within the WGWSS. The planning decisions were categorised into six areas of system operation viz. (i) priorities of supply between different sources of supply and between different user groups; (ii) a storage flood reserve volume to provide flood attenuation; (iii) environmental allocation shares for apportioning environmental water allocations between river basins; (iv) the preference of alternative flow paths for the harvesting and/or transfer of water; (v) storage maximum operating volumes for the key water harvesting storages; and (vi) storage draw down priorities and storage targets. These planning decisions were collectively referred to as an "operating plan."

The constraints of the higher order MOOP were specified both in terms of the formulation of the MOOP (i.e. as bounds on variables and as integer constraints) and also in terms of the real-world limitations of the WGWSS (i.e. as statutory constraints and as physical constraints). By far, most of the problem constraints were configured in the Wimmera-Glenelg REALM model. REALM is a structured computer software package that models the harvesting and bulk distribution of water resources, usually at monthly time-steps, within a water supply system (Perera et al., 2005). It has been developed in close consultation with water managers and practitioners with many enhancements made in response to feedback from these users. As it has also undergone extensive testing and has been used in many practical applications, it is considered to be the modelling standard in Victoria (Australia). One of the major benefits of using an O-S modelling approach is that many of the complexities of a real-world water resources system are already configured in well trusted simulation models.

6.1.2 Development of O-S model

Phase (2) of the proposed multi-objective optimisation procedure involved the development of an O-S model which comprised an optimisation engine and a simulation engine. The optimisation engine was used to perform the search for new candidate optimal solutions and the simulation engine was used to emulate the behaviour of the system under the influence of these new candidate optimal solutions. The process was iterative; simulation outputs were used to calculate performance metric values which were in turn passed to the optimisation engine to search for the Pareto-optimal operating plans by solving the MOOP formulated in Phase (1) i.e. Steps (c) to (e).

The setting up of the simulation engine involved the replacement of an existing REALM model (i.e. WMPP2104.sys file) with a surrogate model that had greater flexibility and stability in terms of changing from one set of operating rules to another; and that had the ability to exchange information between it and the optimisation engine. This lower-fidelity physically based surrogate model was referred to as the Wimmera-Glenelg REALM model and showed a good fit with the WMPP2104.sys file (i.e. Nash-Sutcliffe efficiency index, $E_f = 0.94$). The most significant difference between the WMPP2104.sys file and the Wimmera-Glenelg REALM model was that the latter model had revised many of the carrier penalties that were interfering with the storage targets. Carrier penalties are used by REALM to assign flow path priorities within the water resources system during a simulation time-step. This change resulted in a marked improvement in the stability of the Wimmera-Glenelg REALM model in terms of a reduced number of convergence failures. Note that a failure of a REALM model converging to a solution is an indication that the model setup is not stable. A brief summary was provided in terms of the methodology for the derivation of the hydro-climatic and water demand inputs for the three hydro-climatic conditions viz. historic, low to medium level, and medium to high level GHG emissions. It was explained that there were 9 rainfall inputs, 18 evaporation inputs, and 21 streamflow inputs which represented one of the three hydro-climatic conditions; 30 consumptive water demands; and 6 environment water demands (EWDs).

In addition to writing programming code for the automation of the interactions between the optimisation engine and the simulation engine, the setting up of the optimisation engine itself required a great deal of code writing. The Elitist Non-Dominated Sorting

Genetic Algorithm (NSGA-II) was programmed to interact with the Wimmera-Glenelg REALM model and to iterate towards the Pareto front. The genetic operators of selection, crossover, and mutation were set up to continually evolve and create an offspring of candidate optimal operating plans from a parent population at each iteration of the O-S model. The sorting procedure of the NSGA-II was also set up together with a niching strategy which aided in the creation of a diverse set of operating plans with the continued convergence of the NSGA-II towards the Pareto front. Much focus was placed on the diversity of operating plans along the Pareto front given that in practice it would influence the range of different operating plans that are available for selection by the DM. A greater level of diversity means that the DM has an increased range of operating plans available for the purposes of maintaining/improving the sustainability of the WGWSS, as required. With respect to the optimisation parameters (i.e. genetic operator settings, population size etc), the parameter settings for the O-S model were based on the outcomes of separate studies and confirmed with sensitivity runs using the O-S model.

6.1.3 Selection of preferred Pareto-optimal solution(s)

Phase (3) of the proposed multi-objective optimisation procedure involved the selection of preferred Pareto-optimal solution(s) found by the O-S model developed in Phase (2). However before the process of selection could occur, an analytical procedure was developed in order to evaluate Pareto-optimal operating plans in terms of the sustainability of the system, with respect to all the major interests for water identified in Phase (1) i.e. Step (a). The *evaluation* of Pareto-optimal operating plans in this context refers to the ranking of plans in terms of the sustainability of WGWSS; with respect to all objectives.

The analytical procedure was developed based on a well-established sustainability index developed and refined by Loucks (1997), Loucks and Gladwell (1999), and Sandoval-Solis et al. (2011). Importantly, this Sustainability Index (SI) was used to aggregate all the objectives of the higher order MOOP that were structured hierarchically in Phase (1) i.e. Step (c). The highest level represented the SI which was used to evaluate optimal operating plans with respect to all the major interests for water in the WGWSS. The second level of the SI was expressed in terms of a Component-level Index for the i^{th} interest for water (CI_i) viz. (CI_{env}) for the environmental interests, (CI_{socio}) for the social interests, (CI_{cons}) for the consumptive interests and (CI_{sys}) for the system-wide interests for water. The lowest level of the SI featured the 18 performance metrics which were used to provide the important link between the interests for water in the WGWSS and the search for candidate optimal operating plans. As such, it was shown that the SI provided the basis for the development of optimal operating plans for the WGWSS which had sustainability as an overall goal. Thus, the SI provided a means to rank the Pareto-optimal operating plans in terms of the sustainability of WGWSS. The reasons for using a multiplicative aggregation scheme for the SI were explained with reference to the arithmetic average. The main benefits of this geometric average aggregation were that the SI would have increased flexibility to include a wide range of interests for water and to express these in terms of any number of performance metrics; and that it would have better scaling characteristics so that the SI would not obscure poor performance as compared to the arithmetic average. It was argued that such scaling characteristics would assist the DM to reach consensus amongst competing interests for water by favouring optimal operating plans that had *good* values for all performance metrics (of all interests for water). Additional benefits of using the SI with respect to higher order MOOPs are described in Section 6.2.1.

The process of selecting a preferred optimal operating plan from the Pareto front brought together two aspects of multi-objective optimisation, firstly; the quantitative information regarding the characteristics of the optimal operating plans along the Pareto front; followed by the higher level qualitative information in the form of stakeholders' preferences. The quantitative information was provided by the SI and its ability to evaluate and compare optimal operating plans in both the objective space and the decision space. For this purpose the O-S model was used to find optimal operating plans by solving the higher order MOOP for the three hydro-climatic conditions (i.e. historic, low to medium level, and medium to high level GHG emissions).

With respect to the quantitative information, the O-S model was used to find optimal operating plans by solving the higher order MOOP assuming historic hydro-climatic conditions. The validity of these optimal operating plans was tested against the optimal operating plans found by the O-S model under the two GHG emission scenarios. The dominance test and the SI were used to short list optimal operating plans that were considered robust (i.e. capable of withstanding the changed hydro-climatic conditions given by the two GHG emission scenarios). The results of these robust optimal operating plans are provided in Section 6.2.2.

With respect to the qualitative information, the use of the SI was extended to incorporate the j^{th} stakeholder's weight for the m^{th} performance metric (w_m^j) and a weighted (geometric average) multiplicative aggregation scheme. The resulting Weighted Sustainability Index (SI^j) for the j^{th} stakeholder had all the benefits of the SI in terms of flexibility and scalability as described earlier. Additionally, the SI^j provided continuity in the multi-criterial decision-making process i.e. from evaluation of optimal operating plans through to the selection of a preferred optimal operating plan. For this purpose, the SI^j was applied to the robust optimal operating plans mentioned above assuming three broad categories of preferences viz. (i) strong environmental preferences; (ii) strong social preferences; and (iii) strong consumptive user preferences. The SI^j results for each of the three sets of preferences are provided in Section 6.2.3.

6.2 Conclusions

There are three main conclusions that are drawn from this study, viz; (i) the additional benefits of using the SI in higher order MOOPs; (ii) the results of the O-S modelling runs for the three hydro-climatic conditions (i.e. the robust optimal operating plans); and (iii) the results of the selection process as applied to the robust optimal operating plans.

6.2.1 Additional benefits of using the Sustainability Index (SI) in higher order MOOPs

In addition to the benefits of the SI described in Section 6.1.3 (i.e. flexibility and scalability), this study concluded that the SI provided a visual means to communicate O-S modelling results in both the objective space and decision space. In terms of the objective space, ranking and plotting the SI against its normalised rank provided a visual representation of the Pareto front. The results showed that the gradient of the SI curve represented the diversity of the operating plans with respect to the objective space. A larger gradient represented operating plans which were more diverse than those that produced a section of curve with a smaller gradient. In terms of the decision space, the corresponding decision variable values were plotted together with the SI curve in order to inform the DM about how different planning decisions influenced a system's sustainability.

6.2.2 The results of the O-S modelling runs for the three hydro-climatic conditions (i.e. the robust optimal operating plans)

The higher order MOOP described in Section 6.1.1 was solved (separately) assuming three hydro-climatic conditions, viz; historic, low to medium level, and medium to high level GHG emissions. The validity of the optimal operating plans found by the O-S model under historic hydro-climatic conditions was tested against the optimal operating plans found under the two GHG emission scenarios. The dominance test and the SI were used to short list optimal operating plans that were considered robust (i.e. capable of withstanding the changed hydro-climatic conditions given by the two GHG emission scenarios). For this purpose it was assumed that a robust optimal operating plan met the following two conditions:

1. An operating plan that is optimal (i.e. non-dominated) under the three hydro-climatic conditions. This first condition provided some certainty that one optimal plan (rather than many plans) would be implemented over the planning period; and
2. An operating plan that achieved a higher level of sustainability for the WGWSS (in terms of SI) compared to the current level achieved under the base case operating plan. This second condition provided some certainty that the sustainability of the WGWSS would not deteriorate over the planning period.

The dominance test results together with the SI values showed that the highest ranked SI operating plans found by the O-S model under the three hydro-climatic conditions were indeed robust:

- *Plan no. 11* which was found by the O-S model under historic hydro-climatic conditions was also optimal under the two GHG emission scenarios;
- *Plan no. 49* which was found by the O-S model under low to medium level GHG emissions was also optimal under historic hydro-climatic conditions and medium to high level GHG emissions; and

- *Plan no. 46* which was found by the O-S model under medium to high level GHG emissions was also optimal under historic hydro-climatic conditions and low to medium level GHG emissions.

Interestingly, the simulation modelling outputs (in the form of a water balance) showed that the base case operating plan provided similar consumptive use volumes; the lowest volumes of headworks loss; and the highest total environmental flow volumes under the three hydro-climatic conditions compared to the three robust optimal operating plans. The results for the base case operating plan highlighted the importance of the formulation of the MOOPs, particularly in terms of interests for water that affect all users system wide such as headworks loss.

6.2.3 The results of the selection process as applied to the robust optimal operating plans (i.e. preferred optimal operating plans)

The SI^j was applied to the robust optimal operating plans described in Section 6.2.2 (i.e. Plan no. 11, Plan no. 49, and Plan no. 46) assuming three broad categories of preferences, viz; (i) strong environmental preferences; (ii) strong social preferences; and (iii) strong consumptive user preferences. The SI^j results for each of the three sets of preferences showed that there would be consensus for accepting Plan no. 49 and Plan no. 46 under historic hydro-climatic conditions and that Plan no. 11 would be the most preferred under the two GHG emission scenarios (in terms of the sustainability of the WGWSS). The results of a sensitivity analysis highlighted the importance of the SI^j in terms of (i) informing the DM of the effort that ought to be placed on confirming a stakeholder's uncertainty about their values/priorities; and (ii) increasing the DM's understanding of the way in which stakeholders' preferences affected the SI^j under a range of hydro-climatic conditions.

6.3 Recommendations

This section provides a summary of the recommendations of the study in terms of increasing the fidelity of the Wimmera-Glenelg REALM model; investigating potential developments to the optimisation process using the SI; and the application of the proposed multi-objective optimisation procedure to a real-world planning study.

6.3.1 Increasing the fidelity of the Wimmera-Glenelg REALM model

Over the last decade there has been an increased level of fidelity in the configuration of environmental water demands (EWDs) in the Wimmera-Glenelg REALM model. The term *fidelity* is used in this modelling context to refer to the degree of realism of a simulation model. For instance, in a planning study undertaken in 2006 two EWDs were used to represent the environmental flow requirements for the entire system (i.e. one for the Glenelg River and the other for the Wimmera River). These EWDs were configured as a seasonal pattern which were constant each year subject to the available water in the WGWSS. In years of low water availability the seasonal pattern would be factored down and years of high water availability the seasonal pattern would be factored up (SKM, 2006). By comparison to the EWD setup in the (current) Wimmera-Glenelg REALM model, the level of complexity has increased in terms of the number of environmental flow sites (i.e. four more sites); the variability in the seasonal pattern each year; and the management of the environmental water account in terms of the regulated and unregulated water that is used to supply these demands. Moreover the basis of these EWDs has also increased in sophistication whereby environmental flow requirements place a greater focus on the frequency and duration of daily flow events (Godoy Consulting, 2014).

Arguably, the next step in achieving higher levels of fidelity would be to convert the monthly operating rules within the Wimmera-Glenelg REALM model to a daily time-step with due consideration to the additional factors that arise in day-to-day operation. Incorporating such higher fidelity attributes into the Wimmera-Glenelg REALM model would have represented a major development milestone and taken some time to complete. For instance, it would have needed to be calibrated and validated over a range of climatic conditions in order to ensure that it was capable of replicating the behaviour of the system. Kuczera et al. (2009) highlight that one of the main modelling issues that arise when moving from monthly to daily time-steps is the need to more explicitly account for hydraulic constraints. Moreover, Kuczera et al. (2009) point out that the lack of travel time functionality is also evident in daily models and so this would also need to be addressed in order to avoid producing misleading impacts, particularly under climate change (Kuczera et al., 2009).

Fortunately, one of the advantages of REALM is its ability to represent virtually any constraint imaginable using variable capacity carriers (Perera et al., 2005). These types of carriers are essential for modelling complex storage operating rules and environmental flow rules as was further demonstrated by this study.

6.3.2 Investigating potential developments to the optimisation process using the SI

As explained earlier in Section 6.1, one of the main challenges in many higher order MOOPs is that the dominance test causes slow convergence to the Pareto front. For instance, in the comparison of two very similar performing Pareto-optimal solutions, the solution that has at least one better performing objective would have the effect of dominating the other solution, assuming all other objectives of both solutions are equal. This is the reason for the increase in the proportion of Pareto-optimal solutions to the population size in higher order MOOPs giving rise to the slow convergence to the Pareto front.

Given its ability to rank Pareto-optimal solutions, the SI could be used as part of the optimisation process in order to discard poorly ranked plans (e.g. plans that have $SI = 0$) from the offspring population. However consideration would need to be given to maintaining the population size constant at each iteration following the elimination of these poorly ranked solutions. In addition to the ranking ability offered by the SI, it could be used to measure the diversity amongst Pareto-optimal solutions. This (SI) attribute could be trialled in the NSGA-II as an extension to the niching strategy which solely works in terms of measuring solution diversity (i.e. via the crowding distance metric).

Such investigations into potential developments to the optimisation process would need to be undertaken with a clear rationale together with proven metrics to demonstrate the effectiveness of the SI against other proven strategies.

6.3.3 Application to real-world planning study

A true validation of the proposed multi-objective optimisation procedure would occur with its application to a real-world planning study. This validation would encompass such areas as the elicitation of interests for water and stakeholders' preferences; understanding the uncertainty associated with the inputs and parameters used to find optimal operating plans; and proving that the optimal operating plans found are in close proximity to the Pareto front.

Whilst this study identified the four major interests for water through a desktop study of high quality information, this cannot replace the elicitation of actual interests for water that would be attained through a real-world planning study. Similarly, the criteria by which to evaluate alternative operating plans would in all likelihood vary from agency to agency and from individual to individual. The hierarchical approach to the structuring of the higher order MOOP would also be tested and opportunities for improving and streamlining such would be explored. One such test could be to compare the optimal operating plans found by a MOOP which considered all objective functions versus another MOOP which had a collapsed or aggregated set of the same objective functions. This would be analogous to comparing the 18-objective function MOOP presented in this thesis with a MOOP which considered the aggregation of these objective functions according to their respective interests for water (i.e. environmental, social, consumptive, and system-wide interests). Moreover, the possibilities of increasing the fidelity of the simulation model and of using the SI as part of the optimisation process could be explored.

Similar to the elicitation of interests for water, preferences elicited from real-world stakeholders would also vary widely and efforts would need to be made to consolidate such preferences into workable information for input to the SI^j. Again, this process of incorporating real-world attributes to the problem would have the potential to lead to improvements to the proposed SI^j. Such elicitation of interests for water and stakeholders' preferences could easily be under-estimated and under-valued by this study which used information from recently completed planning studies of the WGWSS.

The next major planning study in the WGWSS is scheduled to occur in 2019. This follows the recent completion of the review of water entitlement arrangements in 2014 (GWMWater, 2014). It is worth noting that this review process was supported by simulation modelling using REALM. Moreover the recommendations of the study were largely concerned with improving system operation in terms of meeting the needs of social interests for water (i.e. the preservation and restoration of recreation amenity); and environmental interests for water (i.e. the development of collaborative management plans for improving environmental watering arrangements between water agencies).

In regards to the uncertainty associated with the inputs and parameters used to find optimal operating plans, it is recommended that an uncertainty analysis be included in the proposed multi-objective optimisation procedure in order to understand the implications of selecting one plan over another. This could be undertaken in terms of quantifying the uncertainty of the data inputs and simulation and optimisation parameters used in the O-S model. Having a better understanding of the uncertainty associated with the optimal operating plans found by the O-S model will provide the basis for more realistic trade-offs among Pareto-optimal plans. Note that this uncertainty analysis would serve to compliment the use of future hydro-climatic projections in the proposed multi-objective optimisation procedure.

Whilst not a focus of this study, the search for optimal operating plans in a real-world study would need to extend beyond 5 generations and demonstrate close proximity to the Pareto front, including a good level of diversity of plans along that front. To that end, it would be recommended to exploit the distributed or shared memory parallel computing architectures that are available in order to provide the high computational effort required to evolve such optimal operating plans. Additionally, this parallel processing approach would assist with addressing (in part) the issue of slow convergence that exists in many multi-objective evolutionary algorithms.

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