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Testing the robustness of optimal operating plans under various future hydro-climatic scenarios

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ABSTRACT

A key challenge for water resources planning processes around the world is to develop operating plans that are optimal under a range of hydro-climatic conditions. The consequences of such long term planning decisions can vary in terms of the social, economic, and environmental impacts. Given these potential impacts, it is important that operating plans are tested under a range of hydro-climatic conditions to ensure that they are sufficiently robust to withstand future changes in climate. The aim of this study is to present a procedure for testing the robustness of optimal operating plans for complex water resources systems using a combined multi-objective optimisation and sustainability assessment approach. The approach embeds an optimisation-simulation (O-S) model which is applied to an 18-objective function multi-objective optimisation problem of the Wimmera-Mallee Water Supply System (WMWSS). The WMWSS is a multi-reservoir system located in Western Victoria (Australia) which is operated to meet a range of competing interests for water using complex operating rules. The O-S model is applied to the WMWSS to search for optimal operating plans over a 100-year period into the future assuming two plausible greenhouse gas (GHG) emission levels. The two GHG emission scenarios represent lower and higher ends of the estimated range of projected GHG emissions, providing a wide range of future hydro-climatic conditions. A robustness test is used to evaluate the validity of the most sustainable optimal operating plans under the two GHG emmission scenarios and also those found previously under a historic hydro-climatic sequence. The test results show that the status quo or base case operating plan is optimal but is neither the highest nor the lowest in terms of the level of sustainability that could be achieved in the WMWSS, under historic and the higher GHG emission scenario. Moreover, the results show that the most sustainable optimal operating plans found under the three hydro-climatic scenarios are sufficiently robust to withstand the full range of hydro-climatic conditions considered whereas the base case operating plan is not as robust. The risks involved in the implementation of operating plans which exhibit large deviations from the base case operating plan are discussed. These risks highlight the importance of problem formulation and sensitivity analysis of the optimal operating plans in order to find real world solutions to real world problems.

Keywords: robustness, sustainability, optimisation, Wimmera-Mallee Water Supply System

INTRODUCTION

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. 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 performance 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).

Present day water planning processes around the world demonstrate 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). The assertion is that sustainable development can only succeed with sustainable water resources systems supporting that development. For this to occur, the MOOP would need 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.

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. While the availability of general circulation models (GCMs) make it possible for planning processes to incorporate the latest advances in the projection of future climate, their coarse spatial resolution do not allow for such predictions at the catchment or local scale. Sachindra (2014) developed various models for the purposes of statistically downscaling this 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).

Godoy et al. (2015) presented a combined multi-objective optimisation and sustainability assessment approach which was used to formulate and solve a higher order MOOP for the Wimmera-Mallee Water Supply System (WMWSS). The WMWSS is a vast and interconnected multi-reservoir system located in Western Victoria (Australia) which is operated to meet a range of competing interests to water using complex operating rules. The MOOP was formulated using 18 objective functions and 24 decision variables assuming historic hydro-climatic conditions. The 2015 study incorporated sustainability performance metrics in such a way that contributed towards the overall sustainable operation of the WMWSS. While the results of this study identified optimal operating plans that were more sustainable than the status quo, it remained to be seen whether such plans could withstand conditions beyond historic. Several robustness frameworks have evolved to meet this challenge. To this end, Herman et al. (2015) proposed a taxonomy of such robustness frameworks to compare such approaches based on their methods of (i) identifying alternatives, (ii) sampling states of the world, (iii) quantification of robustness measures, and (iv) identification of key uncertaintaines (or robustness controls) using sensitivity analysis. Herman et al. (2015) used a regional urban water supply case study in the United States of America to illustrate the decision consequences that emerged highlighting the importance of an informed definition of robustness.

The outcomes of the first review of water entitlement arrangements in the WMWSS was recently published in GWMWater (2018). The aim of the review undertaken in 2014 was to assess the performance of significant changes to these arrangements against 11 storage management objectives after three years of implementation. The key outcome was that the system had indeed been operated in line with the storage management objectives. Moreover, of the 40 recommendations for improvements proposed in 2014, 36 have been completed with four remaining in-progress. Of relevance to the present study is one of the four recommendations regarding the increased maximum operating volume (MOV) for Rocklands Reservoir, from 75% to 85% of full supply volume (348 GL). This storage is the largest in the system and holds many years worth of inflows and so the complex rules which govern its operation are of great importance. It is worth noting that the MOVs for the headworks storages (including Rocklands Reservoir), constituted 6 of the 24 decision variables considered by Godoy et al. (2015).

The aim of the present study is to highlight the importance of robustness testing from an operational standpoint using the WMWSS as a case study. Ideally, water resources planners ought to seek agreement on not only the most sustainable and optimal operating plans but also those that are robust enough to withstand deviations from the conditions for which they were designed. This study applies the same technique used by Godoy et al. (2015) to search for optimal operating plans assuming two plausible future climate scenarios. The future climate scenarios have been previously prepared using the downscaling technique developed by Sachindra (2014). The most sustainable of these plans is assessed in terms of its robustness together with those found under the historic hydro-climatic scenario.

THE WIMMERA-MALLEE WATER SUPPLY SYSTEM

Figure 1 is a schematic of the WMWSS showing 6 environmental water demands (EWDs) and 30 consumptive user demands. Other interests for water in the WMWSS include the provision for recreation amenity and maintenance of water quality at certain storages. Three such storages were selected by Godoy et al. (2015), namely; Lake Lonsdale and Lake Fyans for the provision for recreation amenity (GWMWater, 2012a; 2012b) and Rocklands Reservoir for the maintenance of water quality (GWMWater, 2011). Common to all users of 'regulated' or stored water is the annual and progressive allocation of water that commences in July and ends in June of each year. Regulated water is used for supply to consumptive users, EWDs, and to provide for recreation amenity at certain storages. There are many possible combinations for harvest and supply of water within the interconnected WMWSS. This requires a complex set of rules to move water around the system so that resources are available at the appropriate time and place to meet the needs of all interests for water. The system operator, Grampians Wimmera Mallee Water (GWMWater), described these operating rules in 2016 for the purposes of expressing the status quo in operating rules at that time (GWMWater, 2016).

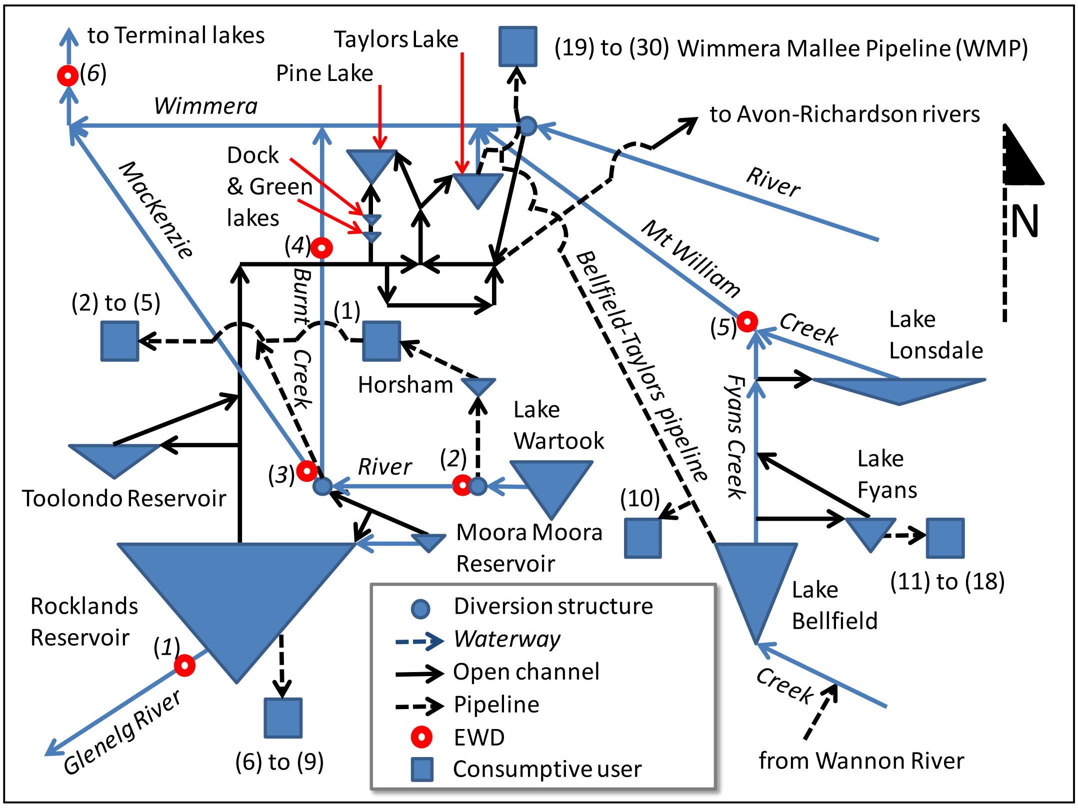

Figure 1. Schematic of WMWSS (not to scale)

One important subset of these rules, are those that govern the MOV for the storages in the headworks. The largest of these storages, Rocklands Reservoir, is located on the Glenelg River and can store up to 348,310 ML. A unique feature is that all entitlement holders are able to be supplied from this single reservoir (GWMWater, 2016). This includes a range of users with many diverse and sometimes competing needs in terms of the management of water quality and access to water, particularly at low storage volumes. The MOV was increased following the completion of the 2013 – 2014 Bulk and Environmental Entitlements Operations Review to improve the operational flexibility of the system whilst reducing uncontrolled spills, evaporation losses and the opportunity of carp entering the Glenelg River downstream of the reservoir. The MOV for the storage was increased from 75% to 85% of full supply volume.

The fundamental operating rule for Rocklands Reservoir is to operate the reservoir up to its MOV throughout the year when practicable. A minimum operating volume of 69,600 ML is also maintained in order to provide (i) stored water for entitlement holders that can only be supplied from the storage; (ii) to buffer poor quality inflows during low inflow years; and (iii) to facilitate suitable recreation levels. Note that this is a desirable minimum and the storage may be drawn down to lower levels under extreme dry conditions. As levels approach the MOV, water surplus to that required to meet entitlement holder demands is actively transferred to downstream reservoirs where space exists (i.e. Taylors Lake or Toolondo Reservoir) or directed to the Glenelg River. GWMWater (2018) explains that in addition to the increased MOV, there is also a need to assess the impact of this increase in terms of the long term average transfer volume to Toolondo Reservoir. The author suggests that this ought to be explored as part of the upcoming 2019 review.

Toolondo Reservoir is an off-stream reservoir with a Full Supply Volume (FSV) of 98,260 ML (GWMWater, 2016). Its purpose is to supply water to the Wimmera Mallee Pipeline (WMP) via Taylors Lake, and to provide for water-based recreation activities. Toolondo Reservoir predominately relies on transfers from Rocklands Reservoir to fill. Toolondo Reservoir is primarily used as a balancing storage, in conjunction with Rocklands, to maximise the efficiency of harvesting from the upper Glenelg River catchment. As the outlet channel at Toolondo Reservoir is high (about 40,000 ML), releases are usually aided by pumping. Therefore, careful consideration is made when deciding when water will be transferred from Rocklands Reservoir to Toolondo Reservoir and prior to releasing water from Toolondo Reservoir. The MOV is about 50% of the FSV, or 50,530 ML, and this effectively limits the volume taken from the Glenelg River catchment.

Taylors Lake is also an off-stream storage with a FSV of 27,060 ML. Taylors Lake has a major role in the water supply system as a secondary source of supply for the WMP and environmental water to the Wimmera River. Taylors Lake is unique in that it is the only storage able to receive water from any other part of the water supply system. Water quality in Taylors Lake can be poor with elevated levels of salinity, turbidity and nutrients. A range of strategies are employed to alleviate the poor quality water in the storage including minimising the harvest of poor water quality by selectively taking water from the lower Mt William Creek (including Lake Bellfield) and MacKenzie River (including Lake Wartook and Moora Moora Reservoir) and routing water through the storage to flush and dilute stored water. To assist in managing water levels during the inflow season, a target curve is followed between the months of April and October inclusive. However, for the purposes of the present study a (constant) MOV of 26,960 ML is assumed all-year round.

For reasons of brevity, it is sufficient to present the outcomes of the present study in terms of the (MOV) planning decisions regarding Rocklands Reservoir, Toolondo Reservoir, and Taylors Lake only. The reader is referred to GWMWater (2016) for further details regarding the operating rules for the other parts of the headworks.

FUTURE HYDRO-CLIMATIC SCENARIOS

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). The Intergovernmental Panel on Climate Change (2000) explains that these global climate projections are based on assumed future greenhouse gas (GHG) emission scenarios and refers to these as Special Report on Emissions Scenarios (SRES). 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 spread of uncertainty around possible future climate.

The fifth and most recent IPCC assessment report (AR5) included a methodological change that reflects the current trends in the climate literature (IPCC, 2014). Since the previous assessment report in 2007, many scientists have drifted towards the consideration of cumulative emissions in climate targets rather than annual emissions. Bowerman et al. (2011) found that the relationship between cumulative emissions and temperature change was nearly linear, meaning that temperature and cumulative emissions increase proportionally to each other. This effectively means that cumulative emissions are the most important factor in explaining temperature change, and so better conceptualises possible futures compared to using annual emissions. With this methodological change, IPCC (2014) revised its naming convention of GHG emission scenarios to ‘Representative Concentration Pathways’ (RCPs). Note that for the purposes of the present study, the aforementioned SRES scenarios are used given the availability of downscaled hydro-climatic datasets for the WMWSS.

ROBUSTNESS FRAMEWORKS

As outlined earlier, Herman et al. (2015) proposed a taxonomy of robustness frameworks to compare such approaches based on their methods of (i) identifying alternatives, (ii) sampling states of the world, (iii) quantification of robustness measures, and (iv) identification of key uncertaintaines (or robustness controls) using sensitivity analysis.

In the simplest cases of identifying alternatives, a set of discrete alternatives may by predefined by the decision maker. This reflects a high degree of knowledge about system performance under uncertainty. In regards to the Wimmera-Mallee region study area, this largely relates to the changes in climate; more recently since 1997 when a step-change reduction of 75% occurred relative to the long term average annual system inflow from 1891 to 1997. The latest operating plan developed by GWMWater (2016) describes a set of operating rules which have been successfully applied over recent times to cope with dwindling water resources over the Millenium Drought and the introduction of changes to water sharing rules in 2010. For the purposes of the present study, this operating plan is referred to as the ‘base case operating plan’ which represents the status quo in operating rules for the WMWSS. In contrast, there are robustness frameworks which have employed a computational search technique such as that used in multi-objective optimisation. The approach presented by Godoy et al. (2015) is an example of such a technique. Herman et al. (2015) highlights a key distinction among the search techniques; namely those that explicitly use a robustness metric as part of the search, and those like Godoy et al. (2015) which do not. The present study uses the same combined multi-objective optimisation and sustainability assessment approach in Godoy et al. (2015) to search for the most sustainable optimal operating plans for the WMWSS. The approach embeds an optimisation-simulation (O-S) model which uses the Elitist Non-dominated Sorting Algorithm (NSGA-II) as the optimisation engine and the REsource ALlocation Model (REALM) software as the simulation engine. The modelling process is iterative; simulation outputs are used to calculate objective function values which are in turn passed to the search engine to find optimal solutions.

As explained by Herman et al. (2015), regardless of whether or not alternatives are predefined or optimised, robustness frameworks are followed by evaluating their performance across a set of uncertain 'states of the world.' Note that the exception is where a robustness metric is explicilty included as part of the computational search technique. The uncertain factors may be those that are well-characterised and those for which probability distributions are not as well understood. Once the uncertain factors are identified, combinations of these can be sampled to create states of the world. Moreover, sensitivity analysis can be used to identify ranges within these uncertain factors which may be particularly influential (in terms of affecting outcomes), regardless of the likelihood of these scenarios. For the present study, the greatest uncertain factor is assumed to be the changes in climate due to GHG emission levels into the future.

Having identified a set of alternatives and evaluated these in a set of uncertain states of the world, it is necessary to quantify their robustness in order to facilitate the decision making process. Herman et al. (2015) pointed out that the choice of robustness measure is not straightfoward and broadly classified these into those of 'regret' and 'satisficing' measures. In general, regret measures quantify the cost (not necesserily monetary) of choosing incorrectly while satisficing refers to the tendency to seek outcomes that meet one or more objectives but may not achieve optimal performance. In regret measures, this can be defined for a single solution as the deviation from its expected performance or from the best solution in the prevailing state of the world. The present study focuses on the latter of these regret approaches using a dominance test on the most sustainable optimal operating plans.

The last and crucial step of the robustness framework is to identify those uncertain factors most responsible for failure to satisfy stakeholder requirements. While Herman et al. (2015) provide a comprehensive review of such sensitivity analysis methods, they highlight two important findings from their work. One is the absence of factor prioritisation or ranking of all uncertain factors in order of their sensitivity; and the other is that sensivity analysis itself is in recent times viewed as a required tool to improve the transparency of model assumptions in policy contexts. For reasons of brevity, the present study does not include this final step but the need for this important work is discussed in terms of those factors which may be responsible for reduced levels of robustness.

A COMBINED MULTI-OBJECTIVE OPTIMISATION AND SUSTAINABILITY ASSESSMENT APPROACH

A generalised procedure for the formulation of MOOPs relating to multi-reservoir systems with complex operating rules was developed by Godoy et al. (2011). The four-step procedure involves identifying (i) *stakeholders' interests to water* (i.e. basis of the MOOP); (ii) the *decision variables* that describe the key operating rules of the water resources system; (iii) the *objective functions* used to guide the optimisation search; and (iv) the real-world limits or *constraints* such as the capacity of storages, channels and pipes etc. It is important to highlight that Godoy et al. (2011) recommended that the objective functions be based on step (i) in order to ensure all stakeholders' interests are explicitly taken into account. Building on this procedure, Godoy et al. (2015) incorporated the sustainability performance metrics proposed by Loucks (1997) i.e. reliability, resiliency, and vulnerability with a view to providing the vital link that is required to ensure all stakeholders' interests are explicitly taken into account in such a way that contribute towards the overall sustainable operation of the WMWSS:

- Component-level Index (CI_i) assumed that the sustainability for the i^{th} interest for water was measured in terms of three metrics viz. reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i).
- Interests for water identified for the WMWSS were broadly classified into four groups viz. environmental (env); social interests ($socio$) 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 (*sys*) water allocations ($alloc$).

Equations (1) to (4) are the Component-level Index for each of these four interest groups as measured by the three abovementioned metrics. Equation (5) is the mathematical expression for the 'Sustainability Index' (SI) which brings together the various CI_i. The reader is referred to Godoy et al. (2015) for further details regarding the basis of these equations.

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

$$CI_{socio} = [Rel_{LL} \times Res_{LL} \times (1 - Vul_{LL}) \times Rel_{LF} \times Res_{LF} \times (1 - Vul_{LF}) \times Rel_{RR} \times Res_{RR} \times (1 - Vul_{RR})]^{1/9} \tag{2}$$

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

$$CI_{sys} = [Rel_{alloc} \times Res_{alloc} \times (1 - Vul_{alloc})]^{1/3} \tag{4}$$

$$SI = \left[(CI_{env})^3 \times (CI_{socio})^9 \times (CI_{cons})^3 \times (CI_{sys})^3\right]^{1/18} \tag{5}$$

Godoy et al. (2015) solved the higher order MOOP using an O-S model which found 56 optimal operating plans. The authors presented the SI values of these optimal operating plans in terms of their normalised rank as shown in Figure 2 and proved that the resulting SI curve was a useful means of evaluating and comparing optimal operating plans in both the objective space and the decision space. Note that this iterative suite of O-S modelling runs or 'scenario' assumed a repeat of the historic hydro-climatic conditions over the period January 1891 to June 2009 at a monthly time-step. This O-S modelling scenario is referred to as Run (A1) throughout this paper. The results showed Plan no. 11 had the highest SI among the 56 optimal operating plans with a value of 0.52. A simulation-only run (referred to as the 'base case operating plan' – BC01) represents the status quo in operating rules for the WMWSS as at 2016 (GWMWater, 2016) and is used as a reference point to show the relative improvement in SI.

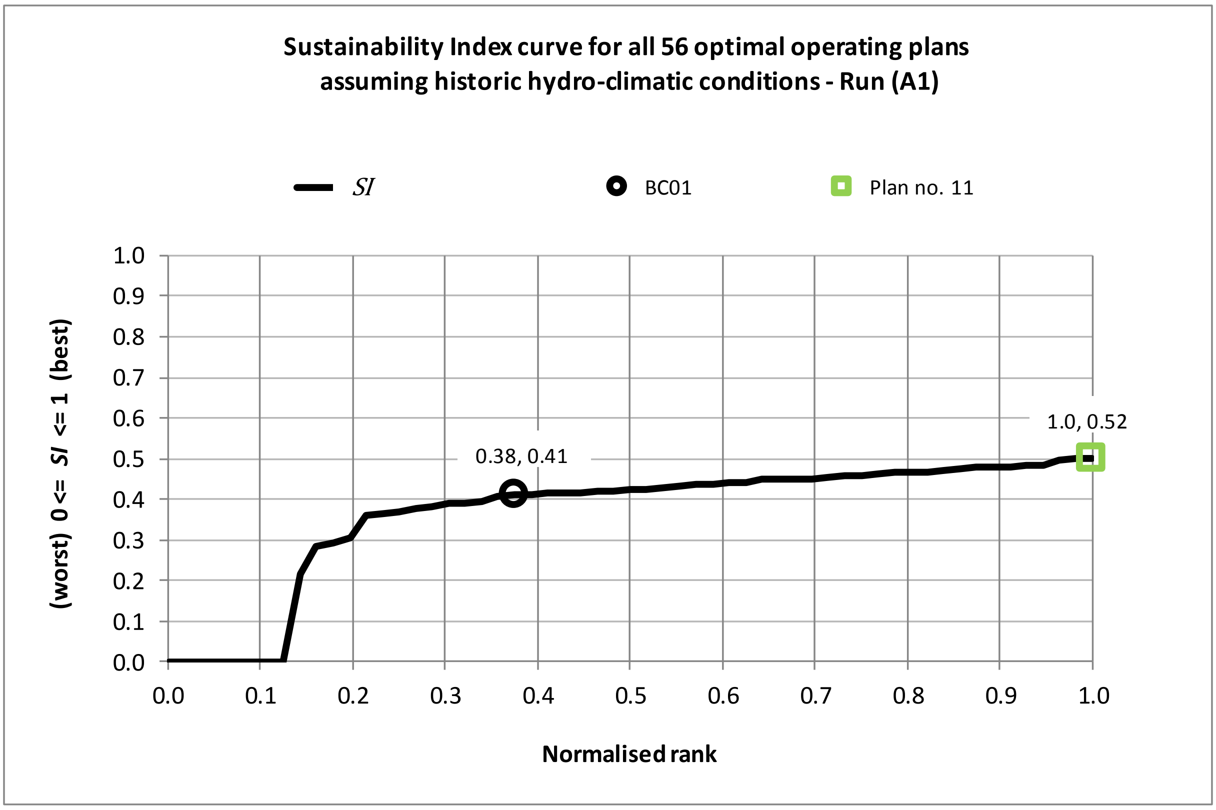

Figure 2. Sustainability Index curve for Run (A1)

A MOOP FOR THE WIMMERA-MALLEE WATER SUPPLY SYSTEM UNDER TWO

PLAUSIBLE FUTURE GHG EMISSIONS SCENARIOS

For the purposes of testing 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 scenario into the future. In regards to the aforementioned robustness frameworks, this section describes the three (of four) steps: (i) identification of alternatives; (ii) states of the world; and (iii) quantification of robustness.

The two scenarios represent the lower and higher ends of the estimated range of GHG emissions as per the SRES described previously. The motivation for choosing these bookend estimates is that robustness testing of optimal operating plans would occur under conditions which potentially cause the largest deviations from historic. The low to medium level and medium to high level GHG emission scenarios (referred to as the 'B1' and 'A2' storylines) 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).

For reasons of brevity, the evaluation of optimal operating plans found under historic hydro-climatic conditions against those 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. Similarly, the analysis of the decision space is limited to the three variables which control the MOVs for Rocklands Reservoir, Toolondo Reservoir, and Taylors Lake only.

Problem formulation and model setup

In Run (A1), the problem was to optimise the system operating rules with regards to 18 competing objectives which considered environmental, social, consumptive, and system-wide interests for water. It was assumed that the sustainability of the WMWSS was measured in terms of reliability (Rel_i), resiliency (Res_i), and vulnerability (Vul_i) for the i^{th} interest for water. Three objectives were assumed to relate to environmental (env) interests for water expressed in terms of environmental flow deficits. Nine objectives related to social ($socio$) interests for water expressed in terms of the volumes held in Lake Lonsdale (LL), Lake Fyans (LF), and Rocklands Reservoir (RR). Three objectives related to consumptive ($cons$) interests for water expressed in terms of supply deficits. Three objectives related to system-wide interests for water expressed in terms of water allocations ($alloc$).

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. Run (A3) is also the same as Run (A1) except that the climate and streamflow correspond to the medium to high level GHG emissions. These utlimately result in a 12% and 16% reduction in the long term average annual inflow under Run (A2) and Run (A3) compared to the historic hydro-climatic conditions respectively. Note that these are quite favourable conditions compared to the period since 1997 (which equates to a 75% reduction on the same basis).

Objective space 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). Note that in the context of the present study, this process is used to quantify the robustness of optimal operating plans.

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:

Solution (x_1) is no worse than solution (x_2) in all objective functions; and

Solution (x_1) is better than solution (x_2) in at least one objective function.

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. As for the outcome under Run (A1), 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. 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 1 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.

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 (BC02)	Run (A2) - Plan no. 8
$Max, f_1 = Rel_{env}$	Reliability of nil environmental flow deficits	6%	6%
$Max, f_2 = Res_{env}$	Resiliency of nil environmental flow deficits	4%	5%
$Min, f_3 = Vul_{env}$	Vulnerability of environmental flow deficits	9%	8%
CI_{env}	*Environmental Component-level Index*	*0.13*	0.14
$Max, f_4 = Rel_{LL}$	Reliability of volume at Lake Lonsdale exceeding 5,379 ML	59%	63%
$Max, f_5 = Res_{LL}$	Resiliency of volume at Lake Lonsdale exceeding 5,379 ML	12%	13%
$Min, f_6 = Vul_{LL}$	Vulnerability of volume at Lake Lonsdale falling below 5,379 ML	34%	33%
$Max, f_7 = Rel_{LF}$	Reliability of volume at Lake Fyans exceeding 1,761 ML	100%	100%
$Max, f_8 = Res_{LF}$	Resiliency of volume at Lake Fyans exceeding 1,761 ML	100%	100%
$Min, f_9 = Vul_{LF}$	Vulnerability of volume at Lake Fyans falling below 1,761 ML	0%	0%
$Max, f_{10} = Rel_{RR}$	Reliability of volume at Rocklands Reservoir exceeding 69,600 ML	83%	100%
$Max, f_{11} = Res_{RR}$	Resiliency of volume at Rocklands Reservoir exceeding 69,600 ML	11%	100%
$Min, f_{12} = Vul_{RR}$	Vulnerability of volume at Rocklands Reservoir falling below 69,600 ML	17%	0%
CI_{socio}	*Social Component-level Index*	*0.54*	0.73
$Max, f_{13} = Rel_{cons}$	Reliability of nil consumptive user deficits	56%	62%
$Max, f_{14} = Res_{cons}$	Resiliency of nil consumptive user deficits	50%	58%
$Min, f_{15} = Vul_{cons}$	Vulnerability of consumptive user deficits	2%	1%
CI_{cons}	*Consumptive Component-level Index*	*0.65*	0.71
$Max, f_{16} = Rel_{alloc}$	Reliability of full water allocations	100%	100%
$Max, f_{17} = Res_{alloc}$	Resiliency of full water allocations	100%	100%
$Min, f_{18} = Vul_{alloc}$	Vulnerability of reduced water allocations	0%	0%
CI_{sys}	*System-wide Component-level Index*	*1.00*	*1.00*
SI	*Sustainability Index*	*0.49*	*0.58*

'f_x' refers to objective function x.
'CI_i' refers to the Component-level Index for the i^{th} interest for water.
'SI' refers to the Sustainability Index for the Wimmera-Glenelg Water Supply System.
* 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.
'Rel, Res, Vul' refer to the reliability, resiliency, and vulnerability performance metrics respectively.
'env' refers to environmental interests for water.
'LL, LF, RR' refer to social interests for water at Lake Lonsdale, Lake Fyans, and Rocklands Reservoir respectively
'$cons$' refers to consumptive interests for water.
'$alloc$' refers to system-wide interests for water.

Table 1.Objective function values, Component-level Index values, and Sustainability Index values for the base case operating plan and Plan no. 8 under Run (A2).

The last row of Table 1 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 1 shows that the base case operating plan is not optimal 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 WMWSS, both individually for each of the four interests for water (in terms of CI) and collectively (in terms of SI).

Figure 3 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). The highest ranked SI operating plans under Run (A1), Run (A2), and Run (A3) are Plan no. 11 ($SI = 0.52$), Plan no. 49 ($SI = 0.66$), and Plan no. 46 ($SI = 0.53$) respectively. The SI curves show that the base case operating plan is neither the highest nor the lowest in terms of the level of sustainability that could be achieved in the WMWSS (in terms of SI). Note that the base case operating plan is not shown on the SI curve for Run (A2) given that it was shown earlier to be dominated by Plan no. 8.

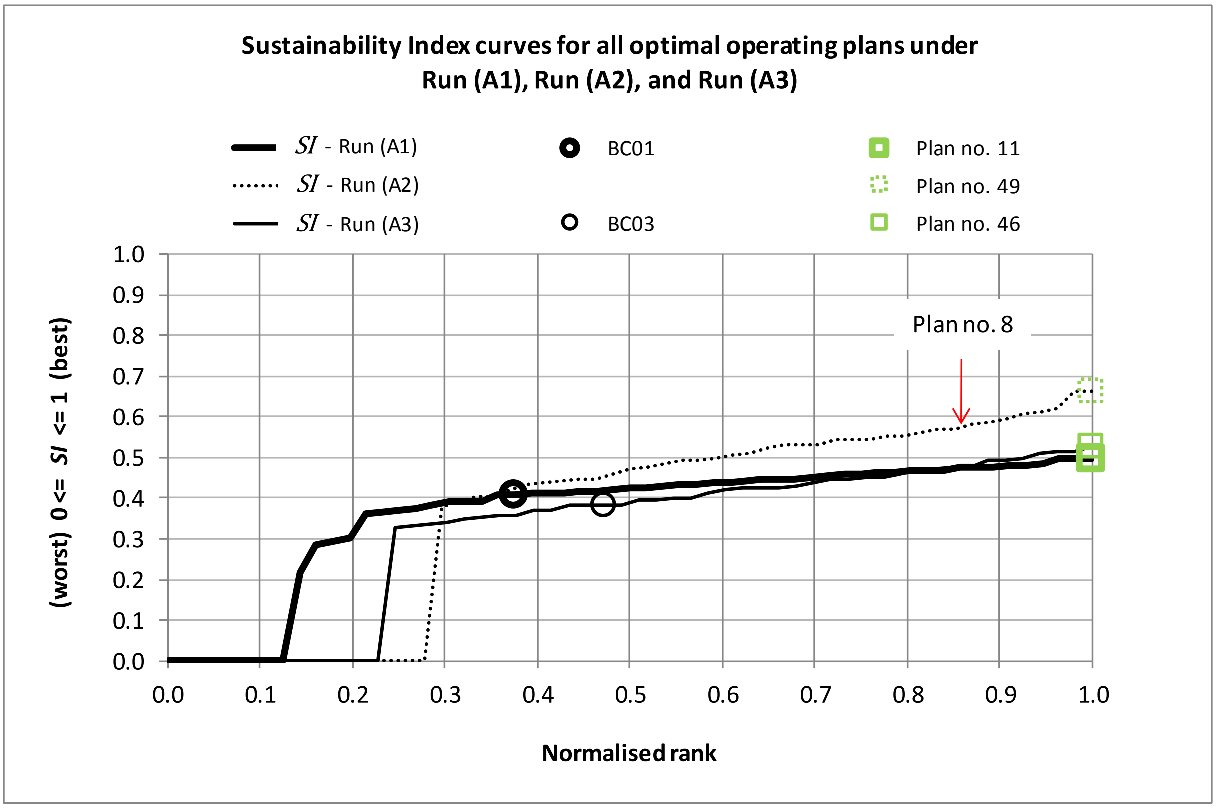

Figure 3. Sustainability Index curves for all optimal operating plans under Run (A1), Run (A2), and Run (A3)

To quantify the robustness of the optimal operating plans found under the various scenarios, the earlier dominance test is applied to the most sustainable (i.e. highest ranked *SI*) optimal operating plans under the three hydro-climatic conditions. That is, Plan no. 11 is tested for dominance under the two GHG emissions; Plan no. 49 is tested under historic and medium to high GHG emissions; and Plan no. 46 is tested under historic and under low to medium GHG emissions. This potentially results in three robust optimal operating plans (i.e. Plan no. 11, Plan no. 49, and Plan no. 46) for each of the three hydro-climatic conditions; a total of 9 plans subject to the outcomes of the dominance test (i.e. 3 plans × 3 hydro-climatic scenarios = 9 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. 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 study, a robust optimal operating plan is defined by the two conditions below. That is, robustness is measured by way of the 'regret' in deviating from the most sustainable optimal operating plan (under all of the future climate scenarios considered).

A robust optimal operating plan complies with the following 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 WMWSS (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 WMWSS will not deteriorate over the planning period.

The results of the dominance tests confirm that the most sustainable optimal operating plans (i.e. Plan no. 11, Plan no. 49 and Plan no. 46) are indeed robust under all three hydro-climatic conditions.

Decision space analysis

Table 2 summarises the results for the three MOVs under the three hydro-climatic scenarios considered. Note that while the base case operating plan did not pass the robustness test, it is included as a useful point of reference. Coincidently, the results show that Plan no. 49 and Plan no. 46 have identical MOVs even though these were found under different GHG emissions. An unexpected outcome is that the MOV for Toolondo Reservoir is less than the corresponding level of the outlet channel (~40,000 ML). This means that any releases from Toolondo Reservoir would need to be pumped incurring additional operational costs compared to the base case opertaing plan.

Storage	**Base case operating plan**	**Run (A1) – Plan no. 11**	**Run (A2) – Plan no. 49**	**Run (A3) – Plan no. 46**
Rocklands Reservoir (FSV: 348,310 ML)	296,000 ML	208,800 ML	243,600 ML	
Toolondo Reservoir (FSV: 98,260 ML)	50,530 ML	46,215 ML	36,972 ML	
Taylors Lake (FSV: 27,060 ML)	26,960 ML	30,330 ML	26,960 ML	

Table 2. 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).

Upon closer inspection of the corresponding simulation results, it is discovered that Plan no. 11 exhibits the least amount of deviation from the base case operating plan. On long term average annual terms, Plan no. 11 would see a 40% reduction in transfers from Rocklands Reservoir to Toolondo Reservoir whereas Plan no. 49 and Plan no. 46 would increase almost 4-fold compared to the base case operating plan, under historic hydro-climatic conditions. The significant increase in the latter plans is accompained by a 50-fold increase in the release from Toolondo Reservoir. Based on operational experience alone, the risk associated with such large deviations from the base case operating plan is expected to be significant under Plan no. 49 and Plan no. 46. On this basis, Plan no. 11 would be considered the preferred sustainable optimal operating plan which is robust under all three hydro-climatic conditions. However, the headworks evaporative and transmission losses for Plan no. 11 are 12% greater (~7,000ML) than the base case operating plan. This is a significant volume in the WMWSS which can be comparable to the magnitude of seasonal shifts in water allocations. Similarly, the headworks losses for Plan no. 49 and Plan no. 46 are 11% higher than the base case operating plan. This highlights the importance of problem formulation and sensitivity analysis of the optimal operating plans in order to ensure any proposed changes to the status quo are practicable.

DISCUSSION

Despite such advances and insights in the projection of hydro-climatic conditions into the future (see for example Safchindra 2014), current water resources planning processes for the WMWSS do not incorporate this climate information. The opportunity for the inclusion of these advances was available as early as 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 WMWSS (GWMWater, 2014). Both these planning studies were supported primarily by simulation modelling over a long-term planning period assuming historic hydro-climatic conditions and two future hydro-climatic conditions referred to as the 'continuation of low flow' and the '2030 climate change' conditions.

The continuation of low flow conditions assume that the flows for all streams in the WMWSS over the period January 1891 to June 1997 are 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 results in a 75% reduction in the average annual inflow to the WMWSS.

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 average annual historic inflow to the WMWSS. This is coincidently similar to the medium to high level GHG emissions scenario (Run (A3)) which equates to a 16% reduction on the same basis.

More recently, the responsible government department has prepared guidelines for assessing the impacts of climate change on water availability in Victoria (DELWP, 2017). Three representative climate change projections were selected from the range of possible climate futures anticipated by 42 different GCMs. The GCM based projections are provided at a river basin scale and for annual changes in climate variables similar to Jones and Durack (2005). This highlights a major difference in that downscaling techniques produce point datasets which tend to better capture the relativities in catchment yields.

Regardless of the hydro-climatic input derivation methodology, the inclusion of a range of hydro-climatic conditions within the robustness testing procedure allows the search for candidate optimal operating plans to be directly 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 procedure developed is that the quanitification of robustness using the dominance test allows for comparisons of a given candidate optimal operating plan to be made under the various hydro-climatic conditions. Moreover, using the SI can help shortlist the quantification of robustness to only those optimal operating plans which are the most sustainable. All these benefits, together with the use of high quality climate projections into the future are consistent with the concept of sustainable development described in the introduction.

The final step of identifying those uncertain factors most responsible for failure in the performance of the optimal operating plans was not captured in this paper and is the subject of future work. This step in the robustness test requires closer examination of the risks and consequences of the various decision outcomes. The present study has highlighted the need to consider the risks of additional pumping costs associated with lowering the MOV for Toolondo Reservoir. It would be prudent to collect this vital information, including any other relevant learnings since the 2014 review, as part of the exploration of alternative operating rules in the upcoming review process in 2019, if possible. As pointed out by Herman et al. (2015), such sensitivity analysis could be used to improve the transparency of model assumptions in that policy context.

In addition to the inclusion of pumping costs, the present study would have also benefited from the inclusion of an objective function which maximised operational efficiency. This together with another objective function for robustness testing could have been used as an alternative approach to the one presented. This highlights the importance of problem formulation and the need to undertake a comprehensive analysis of all interests for water, including the operational efficiency of the system.

CONCLUSIONS

This study presented a robustness test which can be used to identify optimal operating plans that are capable of withstanding a range of future climate conditions. The test used a combined multi-objective optimisation and sustainability assessment approach to search for the most sustainable optimal operating plans using two plausible future hydro-climatic scenarios, and compared these to those found previously under historic conditions (Run (A1)). Low to medium level (Run (A2)) and medium to high level (Run (A3)) greenhouse gas (GHG) emission scenarios were used for this purpose. A simplistic yet effective dominance test of the resulting objective function values provided the basis of quantification of robustness across the three hydro-climatic scenarios. The outcomes of the robustness test of the status quo (or ‘base case operating plan’) and the highest ranked Sustainability Index (SI) operating plans found by the optimisation-simulation (O-S) model 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 WMWSS (in terms of SI). 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 ($SI = 0.52$), Plan no. 49 ($SI = 0.66$), and Plan no. 46 ($SI = 0.53$) respectively.
- The dominance test results together with the SI values showed that the highest ranked SI operating plans were indeed robust under all three hydro-climatic conditions whereas the base case operating plan was not robust given that it was not optimal under low to medium GHG emissions scenario.

Whilst the analysis of the O-S modelling results showed the effect of the three most sustainable optimal operating plans on the four interests for water, it was not possible to ascertain the level of risk associated with the implementation of such plans. Intuitively, it was expected that making large changes to the base case operating rules would inherently impose higher levels of risk and compromise compared to making little or no changes to the status quo. For this reason, Plan no. 11 was considered to be the most preferred among the robust plans given it required the implementation of smaller changes relative to the status quo. 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 decision maker 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.

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