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Optimal Sequencing of Water Supply Options at the Regional Scale Incorporating Sustainability, Uncertainty and Robustness

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Abstract: Planning sustainable urban water supplies requires the use of a long-term planning horizon and multiple criteria for assessment, all of which have inherent uncertainties and difficulties. This paper presents the application of an optimization framework incorporating a post-optimization robustness assessment to the case study of the southern Adelaide water supply system to determine its effectiveness. Various water supply alternatives (i.e. reservoirs, desalination plant, rainwater tank, and water reuse schemes) are considered. Additionally, a 90 year planning horizon and two competing sustainability objectives, including the minimization of economic cost and greenhouse gas emissions, are adopted. In order to determine the robustness of the optimal solutions in the face of a variety of potential future conditions, the sensitivity of the costs and greenhouse gas emissions of the optimal supply sequences is assessed under a range of water supply, population growth and climate change scenarios. The results obtained indicate that there are significant trade-offs between average cost and GHG emissions, but that these trade-offs are relatively robust in terms of GHG emissions under a range of future scenarios. However, there was significant variation in the robustness of the economic costs of the solutions.

Keywords: Sequencing, Urban water resources planning, Sustainability, Uncertainty, Robustness

1 INTRODUCTION

The optimal sequencing of urban water supply sources has traditionally focused on the reservoir expansion problem and economic objectives (Braga *et al.*, 1985; Connarty *et al.*, 1996). However, in recent years, the reliability of traditional water supply sources has been compromised as a result of increasing demand and the impact of climatic factors.

Alternative sources of water, such as desalinated seawater, stormwater harvesting and rainwater tanks have been introduced into water supply systems in order to increase water supply security in times of drought and in response to potential climate change (Coombes *et al.*, 2006). This has increased the complexity of the sequencing process and the frequency at which water supply systems need to be upgraded, as many of the alternative sources of water (e.g. stormwater harvesting) have smaller capacities than traditional sources (e.g. reservoirs).

Moreover, the adoption of sustainability principles has resulted in the need to consider a variety of new assessment criteria in addition to the traditionally used economic criterion. Such criteria include environmental, social and technical elements, as well as temporal scale. This has further increased the complexity of the sequencing task, as sequences that represent optimal tradeoffs between competing objectives need to be determined, rather than just the sequence that minimises economic cost.

Adoption of sustainability principles also requires consideration of extended timeframes in the planning of water resources projects to as long as 50 to 100 years (Mitchell *et al.*, 2007). This amplifies any uncertainties that are present in the sequencing process, both on the demand and the supply side of the equation. This further complicates the development of sequencing plans for urban water sources, particularly given the long design life of water supply infrastructure, as once implemented, it generally lasts for a very long time, so that the impacts of decisions made now will be felt long into the future.

The purpose of this paper is to introduce an optimal sequencing approach that can deal with these issues. The approach extends the method developed by Beh *et al.* (2011a) by incorporating optimization and a robustness-based performance measure (see Beh *et al.*, 2011b) and consists of two stages. Firstly, the problem must be formulated correctly, which includes setting the planning horizon and staging interval, selecting sustainability objectives and choosing potential water supply options. Secondly, the sequencing plan must be developed. This consists of an optimal sequencing process and a post-optimization robustness assessment. The proposed approach is demonstrated using a case study of the southern Adelaide water supply system, which supplies about half of the demand of metropolitan Adelaide.

2 PROPOSED FRAMEWORK FOR THE ROBUST OPTIMAL SEQUENCING OF URBAN WATER SUPPLY OPTIONS

In this section, the overall sequencing framework is introduced, which is able to cater for extended planning horizons, non-traditional sources of water and multiple sustainability criteria, as discussed above.

2.1 Problem Formulation

Selection of Sustainability Objectives

The first step in the problem formulation process is the selection of appropriate sustainability objective(s), O_S to be optimized in the sequencing process (Figure 1). Examples of such objectives include minimising system cost, as well as environmental, and social impacts, while maximising system reliability. To plan for a long time period, the benefits and impacts resulting from developing the supply system are quantified and discounted to current values in order to evaluate the impact on future conditions.

Selection of the Planning Horizon

In this step, the planning horizon, T , needs to be selected (Figure 1). At the same time, the staging interval, t , that is, the length of time between decision points in the sequencing plan must be established. This interval needs to reflect a realistic period for the assessment of planning decisions and the design life of the supply options.

After the planning horizon and staging interval have been defined, the number of decision stages, D_C can be computed by dividing the planning horizon by the staging interval. At each stage, decisions are made about which of the water supply options will be introduced or expanded, and the corresponding capacity accounted for, as

illustrated in Figure 2. For each option, a set of capacities is considered. This means that within each staging interval, each supply option can take any discrete capacity value ranging from its current capacity to a maximum possible value. A constraint set at each decision stage is that the supply must be sufficient to meet the demand, recognizing that there will be changes in both demand and supply over time.

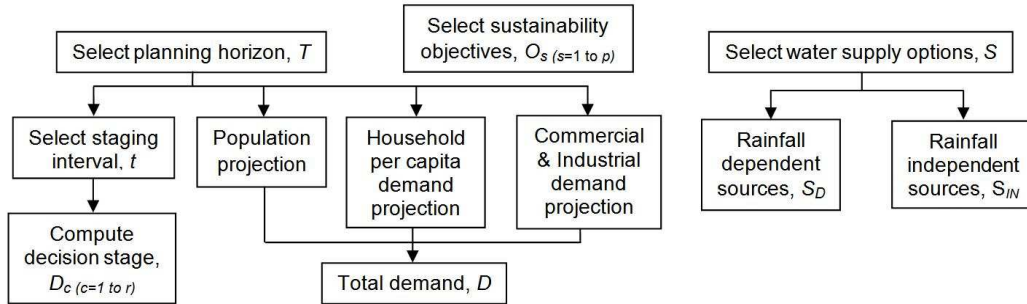


Figure 1 Problem formulation process

Selection of Potential Water Supply Options

Sequencing to safeguard regional water supply involves various water supply options, S . These are the means by which water is sourced for supply to consumers (see Figure 2) and can include dams, desalination plants, harvested stormwater and water tanks, all of which need to be incorporated into the sequencing process. Water supply options, S are categorized into rainfall dependent and independent sources. Reservoirs, stormwater, groundwater and tanks are all dependent sources, S_D . Examples of independent sources, S_{IN} include desalination plants and wastewater reuse.

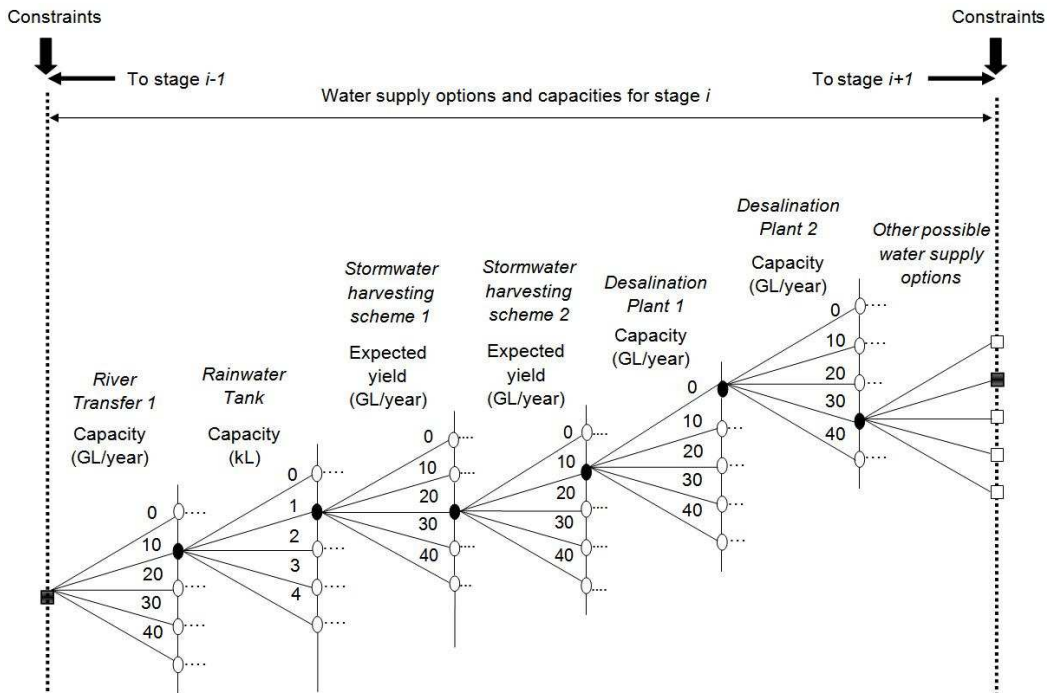


Figure 2 Flow diagram of one possible combination of water supply and capacity options selected at one decision point

2.2 Optimal Sequencing Process Incorporating Robustness

The proposed process of optimal sequencing is shown in Figure 3.

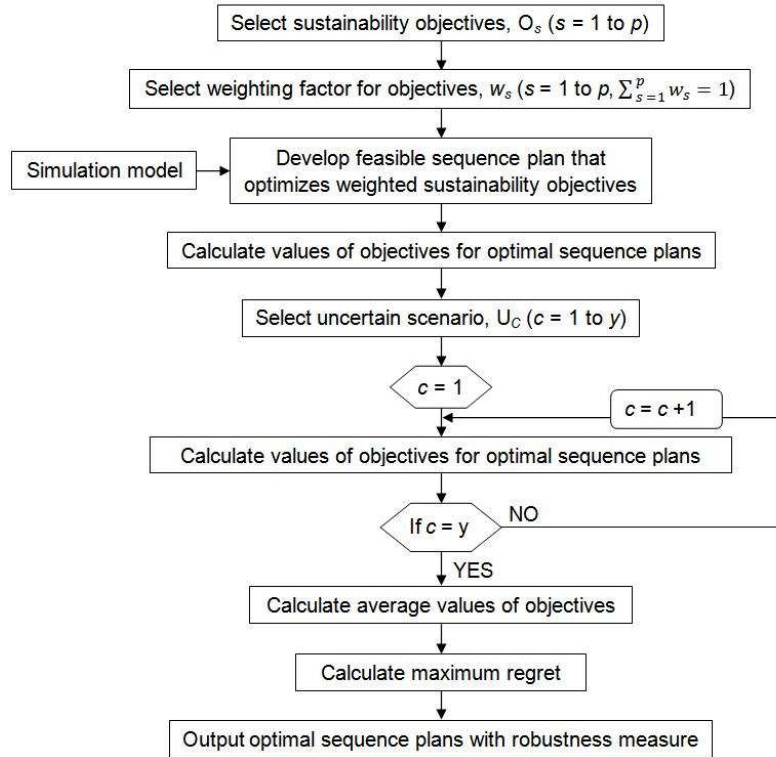


Figure 3 Optimal sequencing process incorporating robustness measure

Firstly, sustainability objectives, O_s (e.g. economic cost and GHG emissions) are chosen to be optimized during the sequencing process (Figure 3). It is common that the sustainability objectives for the sequencing of water supply options are conflicting, which means that achieving the optimum for one objective requires some compromise on one or more of the other objectives. For the proposed sequencing approach, these conflicting objectives are accounted for by using the weighting method (Rangaiah, 2009). This requires the selection of weighting factors, w_s for each of the objectives that reflect their relative importance. It should be noted that the values of the weights can range from 0 to 1, but the sum of the weights has to equal 1. Once the sustainability objectives and weighting factors have been selected, an optimal sequence plan is generated by running an appropriate optimization algorithm in order to select a water supply sequence that optimizes the sum of standardized values of the weighted objectives. The feasibility of each sequence, that is, whether supply meets or exceeds demand at each decision point, is checked using a simulation model of the water supply system under consideration. Then, the values of the objectives are calculated for the final, optimized sequence plan. Next, possible scenarios representing uncertain future conditions, for example, climate change, electricity price changes and population growth, U_c , are selected and the values of the objectives of the optimized sequence plan are calculated for each of these scenarios to enable the robustness of the optimized plan to be determined. It should be noted that as part of

this process, each of the objectives of infeasible sequence plans are penalized in proportion to demand shortfall.

Next, the average values of the objectives and the robustness values of the feasible sequence plans are calculated for the scenarios considered. It is proposed to use maximum regret as the measure of robustness, as suggested by Cui *et al.* (2010) and Beh *et al.* (2011b). Maximum regret is a measure of the maximum variation of the value of each objective over the scenarios investigated, which are all considered equally likely, and is given by:

$$R_x = \max_y [C_{xy} - L_y] \quad (1)$$

$$L_y = \min_x [C_{xy}] \quad (2)$$

where, R_x is the maximum regret associated with sequences x ; C_{xy} are the values of each of the objectives of sequences x when they are assessed over scenarios y ; L_y is the sequence with the best value of each of the objectives for scenarios y . This enables the tradeoffs between average and maximum regret values of the objectives over the uncertain scenarios to be examined for solutions that are optimized for different weightings of the objectives.

3 CASE STUDY

The proposed approach was applied to the case study of the southern Adelaide water supply system, which supplies about half of the demand of metropolitan Adelaide, which is the capital of South Australia and has a population of about 1.2 million. The system consists of three reservoirs: Mount Bold, Happy Valley and Myponga. In addition, there are transfers from the River Murray via the Murray-Onkaparinga pipeline, a desalination plant, existing and potential stormwater harvesting schemes, and household rainwater tanks. Further details of the case study system are given in Beh *et al.*(2011a).

For the case study, the selected objectives include economic cost and GHG emissions from the construction and operation (mainly due to pumping) of the selected water supply options themselves, and weighting factors, $w_1 = 1.0$ and $w_2 = 0.0$; $w_1 = 0.5$ and $w_2 = 0.5$; and $w_1 = 0.0$ and $w_2 = 1.0$ were used. A staging interval of five years was adopted, as the design life of system components is likely to be greater than five years, and this time period allows for regular review of plans in the light of changing system variables, such as rainfall and costs. Consequently, there are 18 decision stages over a 90 year planning horizon. In addition, the population for the case study region was estimated to be 597,000 with moderate annual growth of 0.86% (Australian Bureau of Statistics (ABS), 2008).

For the sequencing process, rainfall dependent sources (i.e. water from two local catchments, transfers from the River Murray and stormwater and rainwater harvesting) and rainfall independent sources (i.e. 100GL and 50GL desalination plant) were considered. The impact of climate variability on the rainfall dependent sources was taken into account in the case study, as detailed in Beh *et al.*(2011a). The simulation model, *WaterCress* (Water-Community Resource Evaluation and Simulation System) (Clark *et al.*, 2002) was used to determine the long-term average yield from reservoirs, stormwater harvesting schemes, rainwater tanks and desalination plants. In addition, the generalized reduced gradient nonlinear optimization algorithm was used to generate the optimal sequence plans for the case study.

It is important that the uncertain scenarios used in the regret calculations provide realistic representations of actual phenomena or crises likely to affect the performance

of sequencing plans in terms of economic cost, GHG emissions or meeting future demands. Thus, for the case study, the post-optimization robustness assessment was carried out for all possible combinations of the scenarios discussed below.

Transfer from the River Murray

From 2002 to 2006, the average amount of water pumped from the River Murray to supply metropolitan Adelaide was 109GL/year (SA Water, 2007), but it is anticipated that the salt content of the water will make it undrinkable 40% of the time by 2020 (Conservation Council of South Australia, 2008). Assuming total supply is evenly distributed between the northern and southern Adelaide water supply systems, the southern system is allowed to take 30GL/year from the River Murray. However, it is possible that supply from the River Murray will be terminated altogether from 2025 to comply with the South Australian Government's aim of reducing reliance on the River Murray and restore the river's health (Government of South Australia, 2009). Consequently, two scenario options were considered, including supply of 30 GL/year from the River Murray over the entire planning horizon and cessation of this supply in 2025.

Population growth

According to the Australian Bureau of Statistics (ABS), South Australia (SA) is projected to reach 2.2 million people by 2056 (Australian Bureau of Statistics (ABS), 2008). However, the SA government is expecting two million people by 2030 (Rivetts, 2008). So, population projections with low and high levels of population changes (i.e. 0.83% and 1.18% of annual growth) were considered.

Climate change

Climate change is affecting rainfall patterns in South Australia (Hughes, 2003) and will influence the yield of rainfall dependent sources in the southern system (i.e. reservoirs, stormwater harvesting schemes, and rainwater tanks). Hence, zero and moderate climate change scenario options were considered. For the latter, climate-affected rainfall data were generated using CSIRO's OzClim (www.csiro.au/ozclim/), a tool created for the scientific research community and policy makers. Moderate mean rainfall and global warming rate were assumed for the next 90 years, thus the ECHAM5/MPI-OM GCM model with the A1B emission scenario was used.

4 RESULTS AND DISCUSSIONS

The optimal values of cost and GHG emissions obtained for the sequenced plans optimized with the different weightings, as well as the sensitivity of these values under the eight future scenarios considered, are given in Figure 4.

As can be seen, the average present value of cost of the sequence plans optimized for cost (i.e. when $w_1=1$ and $w_2 = 0$) is \$685.69 million, with an average present value of GHG emissions of 6.58 megatonnes (MtCO₂-e). The average present value of the sequence plans optimized for GHG emissions (i.e. when $w_1=0$ and $w_2 = 1$) is \$794.86 million, with GHG emissions of 6.01MtCO₂-e, which is an increase of 14% in cost and a reduction of 9% in terms of GHG emissions compared to the sequence plan with optimized cost. The sequence plan optimized for cost and GHG emissions (i.e. when $w_1=0.5$ and $w_2 = 0.5$) has intermediate values for both objectives (i.e. an average present value of \$ 742.85 million and 6.22 MtCO₂-e).

The sequence plan optimized for GHG emissions has the lowest maximum regret in terms of cost, with a present value of \$143.25 million and the sequence plan optimized for cost and GHG emissions has the highest maximum regret in terms of cost, with a

present value of \$303.04 million. The maximum regret of all three sequence plans in terms of cost is reasonably high over the scenarios considered, indicating that the optimal sequence plans are moderately robust in terms of cost over the scenarios considered. The sequence plan optimized for cost and GHG emissions has the lowest maximum regret in terms of GHG emissions, with a present value of 2.35MtCO₂-e, although the variation in regret is relatively small for all three sequence plans, indicating that the optimal plans are quite robust in terms of GHG emissions over the scenarios considered.

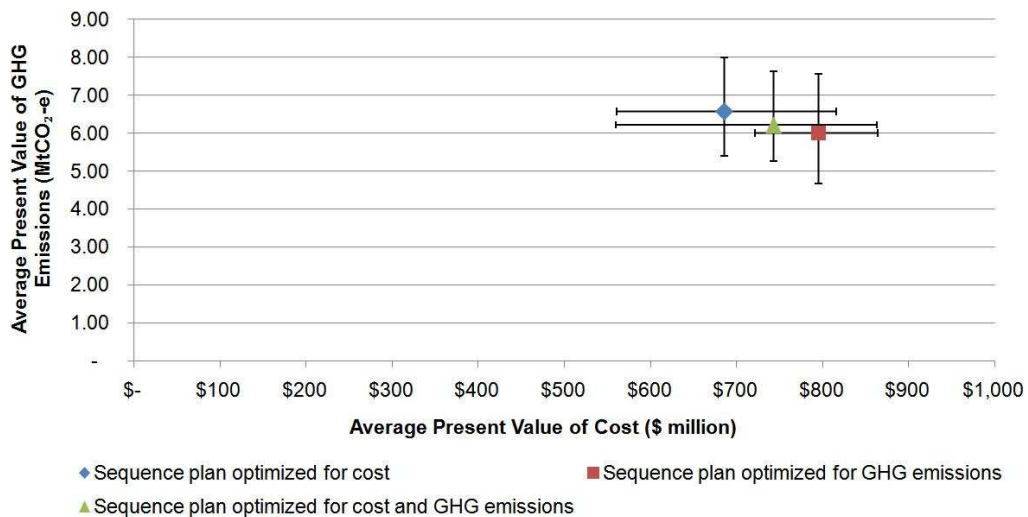


Figure 4 Average and range of cost and GHG emissions for the sequence plans generated for the eight scenarios considered.

5 CONCLUSION AND RECOMMENDATION

The approach presented in this paper incorporates sustainability, alternative water supply sources and robustness into the sequencing of water supply projects at the regional scale. This includes adopting a long-term planning horizon because the promotion of the sustainability of systems entails maximising the benefits of multiple sustainability objectives into the indeterminate future. Long term planning horizons result in increased uncertainties associated with the unforeseen future, which requires the development of robust solutions to best cope with a variety of potential future conditions. This is achieved by considering the trade-off between average values and maximum regret values of the objective functions over a range of uncertain future scenarios.

The proposed approach was applied to the case study of the southern Adelaide water supply system, and demonstrated that the proposed methodology is effective for the sequencing of water supply options at the regional scale incorporating sustainability, alternative water supply sources and the uncertainty associated with long planning horizons. The results obtained validate that the sequence plans optimized for cost consist of a mixture of water sources with lower construction and operating (i.e. pumping) costs but result in higher GHG emissions; however, sequence plans optimized for GHG emissions include a mixture of water sources with lower GHG emissions (i.e. calculated based on building materials and energy) but higher cost. Additionally, the results indicate that there are significant trade-offs between average cost and GHG emissions, but that these trade-offs are relatively robust in terms of

GHG emissions under a range of future scenarios. In contrast, there was significant variation in the robustness of economic cost for different solutions.

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