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Considering sustainability in the planning and management of regional urban water supply systems: A case study of Adelaide's Southern system

Paton F.L.[1], J.P. Baulis[1], B.S. Staniford[1], H.R. Maier[1] and G.C. Dandy[1]

[1] *The School of Civil, Environmental and Mining Engineering, The University of Adelaide, South Australia*
Email: fpaton@civeng.adelaide.edu.au

Abstract: A major challenge this century is to identify ways to reliably supply water to urban areas under the increasing pressures of population growth, urbanisation and climate change. A proper consideration of sustainability is the key to solving the urban water supply system (UWSS) problem, as it ensures that a holistic approach is taken, whereby the economic, environmental, social, technical and temporal aspects of the problem are considered. Substantial research in this field has been undertaken up to this point in time, but this has largely focused at the local and unit scales (urban clusters and individual houses, respectively), rather than the regional scale (cities and towns). There is a wide range of centralised and decentralised supply types that can be implemented at the regional scale, both conventional and non-conventional. Traditionally, conventional water supply types, such as reservoirs, dams, rivers and groundwater, have been used. However, as some of these water supplies have been over-allocated and contaminated, alternative water supplies have been developed, namely household rainwater tanks, aquifer storage and recovery, grey and black water reuse systems, stormwater reuse and desalination plants.

This study presents an approach to sustainability assessment of UWSSs at the regional scale, which is applied to Adelaide's Southern water supply system. The social aspect is accounted for by exploring water allocation policies and the economic and environmental aspects of sustainability are considered by calculating the economic cost and greenhouse gas (GHG) emissions for each potential supply type, which are then combined to formulate total economic costs and GHG emissions for the UWSS. Social discounting of the economic costs and GHG emissions account for the temporal dimension of sustainability, as does a long-term planning horizon of 52 years. Finally, the technical aspect of sustainability is accounted for by a risk based performance assessment, whereby the reliability, resilience and vulnerability of the UWSS are determined.

Potential supply types for the case study include reservoir supply, a desalination plant, River Murray supply and household rainwater tanks. The approach requires a water simulation model to balance the demand and supply of the potential supply type configurations and check that constraints, such as reservoir capacites and pumping limits, are upheld.

Results obtained indicate that by 2060, additional water supply is required to meet the demand of the Southern system and that this would be most appropriately sourced from the River Murray because it has the lowest cost, produces the lowest GHG emissions and results in high technical performance of the system. However, because of future uncertainty over River Murray supply, water planners should also consider alternatives, such as a desalination plant and household rainwater tanks. Desalinated water was found to be cheaper but produce more GHG emissions per KL than rainwater. In terms of the risk based performance of the system, desalinated water was generally preferable to rainwater due to the high variability of Adelaide's rainfall. However, installing small 5KL rainwater tanks was found to greatly improve the technical performance of the system.

Keywords: *urban water supply, sustainability, risk based performance, greenhouse gas emissions, planning and management*

1. INTRODUCTION

Around the world and especially in Australia, the world's relatively limited freshwater resources are stressed due to increases in population growth, urbanisation and climate change, presenting the major problem of how to reliably supply water to urban areas. A proper consideration of sustainability is the key to solving the urban water supply system (UWSS) problem, as it ensures that a holistic approach is taken, whereby the economic, environmental, social, technical and temporal aspects of sustainability are considered.

A number of studies have considered the need to incorporate sustainability into the planning of regional UWSSs. The social aspect is rarely detailed explicitly because it is inherent in the UWSS problem that human demands are at the centre of UWSSs. However, in some cases, social aspects, such as water allocation policies, have been included in studies through scenario analyses (Zongxue *et al.*, 1998; Yamout & El-Fadel, 2005; Pulido-Velaquez *et al.*, 2006). Furthermore, various indicators have been developed to measure the economic, environmental and technical aspects of sustainability. Economic costs of UWSSs are predominantly used to account for the economic aspect, numerous indicators have been used for the environmental aspect, such as environmental flow requirements (Pulido-Velaquez *et al.*, 2006), resource depletion (Yamout & El-Fadel, 2005) and greenhouse gas (GHG) emissions (Peters & Rouse, 2004; Sahely *et al.*, 2005) and the most commonly used technical indicator is risk based performance assessment (Zongxue *et al.*, 1998; Fowler *et al.*, 2003; Sahely *et al.*, 2005).

In UWSS studies, the temporal aspect is the least developed dimension of sustainability. Embedded in the definition of sustainability is the concept of intergenerational equity and consideration of future generations (Brundtland, 1987). Therefore, to incorporate the temporal aspect into sustainability assessment, studies should consider long-term planning horizons. However, this is poorly explored in regional UWSS studies incorporating sustainability. Voivontas *et al.* (2003) and Yamout & El-Fadel (2005) use planning horizons of 30 years and Lundie *et al.* (2004) examine a 20 year scenario, but as Mitchell *et al.* (2007) state, a 20-30 year planning period is too short to adequately account for the different lifetimes of UWSS assets. They suggest using a longer time frame of 50-100 years, supporting the notion that temporal horizons must be expanded from years to decades in order to achieve sustainable development (Sahely *et al*., 2005).

Furthermore, when dealing with future scenarios, it is important that economic and social costs that occur in future years are appropriately discounted so that they can be compared in terms of their present value. Of the studies that examine future scenarios, Voivontas *et al.* (2003) and Yamout & El-Fadel (2005) use Present Value Analysis (PVA) to discount future costs. However, studies of regional UWSSs incorporating sustainability have not yet used social discounting for environmental indicators.

The overall objective of this study is to address the shortcomings of previous research in this field by conducting a sustainability assessment of Adelaide's Southern water supply system. This includes developing an approach that investigates water allocation policies (social aspect), economic cost (economic aspect), GHG emissions (environmental aspect), risk based performance (technical aspect) and a long-term planning horizon (temporal aspect). The temporal aspect is further developed through the inclusion of social discounting of both the economic costs and GHG emissions. This case study illustrates the potential trade-offs in sustainability aspects when using different water supply types, which can help water managers to make better-informed and more sustainable decisions when planning Adelaide's Southern water supply system. While this study is concerned with a specific case study of Adelaide's Southern water supply system, the approach presented can be easily applied to other regional UWSSs.

2. CASE STUDY

Metropolitan Adelaide's water supply and storage is a complex regional urban water supply system of reservoirs, pipelines and catchment areas, which is divided into two sections; the Northern system and the Southern system. The Southern system caters for approximately half of Adelaide's water demand. Existing reservoirs include Mount Bold Reservoir (MB), Happy Valley Reservoir (HV) and Myponga Reservoir (Figure 1). As all water from MB must flow through HV and its associated water treatment plant, for simplicity, MB and HV are treated as a single reservoir. Water pumped from the River Murray via the Murray-Onkaparinga pipeline is also an existing water supply (Figure 1).

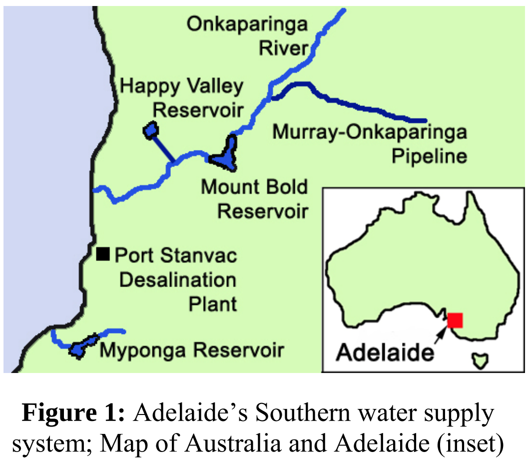

Figure 1: Adelaide's Southern water supply system; Map of Australia and Adelaide (inset)

In addition, a proposed desalination plant at Port Stanvac (Figure 1) and rainwater tanks at the household scale used for garden watering and toilet flushing are considered in this study. Although there are other supply types that are feasible for Adelaide's Southern system, such as stormwater and recycled water, these were considered beyond the scope of this study as there was insufficient information regarding their associated economic costs and GHG emissions.

Historical daily rainfall and evaporation data for the Adelaide and Mount Lofty Ranges were used, but adapted for the effects of climate change based on the CSIRO Mark 3.5 Climate Model (BOM, 2008). Climate change effects were incorporated through a straight percentage reduction in rainfall and evaporation. This approach was considered adequate for the purposes of this study, although the authors acknowledge that there are more sophisticated methods available (for example statistical downscaling). The rainfall and evaporation reductions were based on medium emissions scenario A1B, which assumes an intermediate level of adaptation to new and efficient technologies (IPCC, 2007).

3. METHODOLOGY

Figure 2 details an approach that accounts for the five aspects of sustainability, which was used to assess future plans for Adelaide's Southern water supply system.

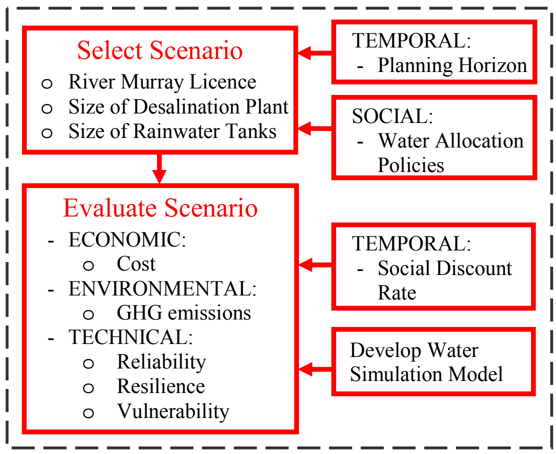

Figure 2: The approach used for the case study

3.1. Select Planning Horizon

The first step (Figure 2) is to select the planning horizons to be considered. The case study was run for a single planning horizon of 52 years (up to year 2060). For this timeframe, a constant demand was calculated based on population projections for Adelaide and individual per capita consumptions. Individual consumptions incorporated permanent water restrictions and projected savings due to government measures and an increase in the use of water efficient technologies. By 2060, the demand for Adelaide's Southern supply system was estimated to be 140GL/yr.

3.2. Select Scenario

The second step is to select the scenarios (in terms of varying the water provided by each supply type), to be implemented as part of Adelaide's Southern water supply system. These were based on various government plans and water allocation policies (Figure 2).

There are State Government plans for a 150ML/day desalination plant to be built at Port Stanvac, with the potential to upgrade to 300ML/day. Assuming that water supplied by the desalination plant will be evenly distributed over Adelaide and given that the Southern system accounts for approximately half of Adelaide's demand, the size of the desalination plant was effectively scaled down to 75ML/day for the current design and 150ML/day for the upgraded design in this study. Hence, these two possibilities were considered as potential scenarios (Scenario 1 & Base scenario respectively, Table 2). Furthermore, as there is no certainty as to what percentage of the desalination plant will be diverted into the Southern system by 2060, a 300ML/day plant (100% of the total capacity of the upgraded plant) was also considered (Scenario 2, Table 2).

The amount of water that can be extracted from the River Murray for the Southern system was based on Adelaide's River Murray water licence and the assumption that River Murray supply is evenly distributed between Adelaide's Southern and Northern supply systems. Currently, pumping from the River Murray is restricted to 130GL/year for the whole of Adelaide (ANRA, 2007), which corresponds to 65GL/year for the Southern system (Base scenario, Table 2). However, in past years, the river has been highly regulated to cope with natural climate variability and to meet the economic and social needs of various stakeholders, resulting in reduced flows and decreasing river system health. As a result, River Murray licences have been reduced significantly. Thus, as detailed in Table 2, a scenario that limits the River Murray supply to 32.5GL/yr for the Southern system (only 50% of the current licence) was examined (Scenario 3, Table 2). Furthermore, in 2008, the South Australian government purchased an additional 30GL of River Murray water at a cost of $14million to secure Adelaide's water supply for the short term. Thus, a final scenario was developed, whereby additional water required above the 65GL/yr licence (up to 80GL/yr maximum) could be bought at a price of $0.47million/GL (Scenario 4, Table 2).

Currently, 40% of Adelaide households have a rainwater tank connected to their rooves (ABS, 2007). However, no reliable information as to the volume of the tanks, the use of the tanks or what percentage of roof runoff is connected to the rainwater tank is available. Furthermore, it is suspected that a large number of rainwater tanks are not connected in-house and only have small yields. Therefore, a conservative approach is taken in this study with regard to rainwater tanks; for the Base scenario (Table 2), households were assumed not to have a rainwater tank and in alternative scenarios, rainwater tanks of 5, 15 and 30KL were assumed to be installed for all households (Scenarios 5, 6 & 7 respectively, Table 2). In all scenarios, rainwater is assumed to be used outside for garden needs and in-house for toilet flushing.

3.3. Evaluate Scenario – Economic Cost and GHG Emissions

Next, economic cost and GHG emissions per KL of water produced by each supply type were estimated (Figure 2). GHG emissions were calculated using a life cycle assessment (LCA), which is a method that evaluates environmental implications of products, processes, projects or services throughout their life cycles, from extraction of raw materials through to the end of life stage (Fava, 1991). Both capital and ongoing costs and GHG emissions were considered for all supply types. The exceptions were reservoirs and River Murray supply, for which the costs and GHG emissions associated with capital works were excluded as the infrastructure associated with these supply types already exists. In order to account for the temporal dimension of sustainability, the ongoing costs and GHG emissions were discounted. Rambaud and Torrecillas (2005) suggest that for private projects, market interest rates or investment rates of return are used to compute the discount rate for economic costs, whereas for public projects a discount rate based on a social-cost benefit analysis is more appropriate. Thus, due to the public nature of this study, a social discount rate was used to discount the economic costs, as well as the GHG emissions.

Gamma discounting was applied to ongoing economic costs because, as Weitzman (2001) suggests, this enables the discount rate to change with time (Table 1), which allows greater emphasis on near future costs than distant future costs. In *The Stern Review on the Economics of Climate Change*, a social discount rate of 1.4%p.a. is applied, which accounts for the costs and feasibility of abating GHG emissions at around 550ppm (avoiding catastrophic climate change) over a long-term planning horizon (Weitzman, 2007). Hence, 1.4%p.a. was applied to discount GHG emissions in this study.

Table 1: Weitzman's recommended discount rate

Time Period	Marginal Discount Rate
Within 1 to 5 years	4%
Within 6 to 25 years	3%
Within 26 to 75 years	2%
Within 76 to 300 years	1%
Within more than 300 years	0%

3.4. Evaluate Scenario – Reliability, Resilience and Vulnerability

According to Hashimoto *et al.* (1982), system performance focuses on system failure, which is defined as any output value in violation of a performance threshold and is described using the three risk based performance indicators; reliability (1), resilience (2) and vulnerability (3). In order to evaluate system performance for the case study, a failure was said to occur in a particular year if demand exceeded supply at any time during that year.

$$Reliability = \frac{T_s}{T_t} \quad (1)$$

Where: T_s = Total time supply exceeds demand (success state)
T_t = Total time period evaluated

$$Resilience = \frac{1}{\left[\sum_{i=1}^{N} T_i \Big/ N\right]} \quad (2)$$

Where: T_i = Period of time that demand exceeds supply (failure state)
N = number of times demand exceeds supply (failure state)

$$Vulnerability = M_{max} \quad (3)$$

Where: M_{max} = Maximum amount by which demand exceeds supply

3.5. Develop Water Simulation Model

The water simulation model is required to balance the demand and supply of the system and check that constraints, such as reservoir levels and pumping limits, are upheld. The simulation model used was WaterCress (Creswell *et al.*, 2002) because (a) it considers water quality, which is of critical importance when comparing different demand types, such as drinking water and garden water, (b) it models both the unit scale (individual demands; internal house supply) and the regional scale (cities; towns), (c) it can be modified easily for different scenarios and (d) it can be run for a daily time step over the simulation period. The WaterCress model for this study consisted of a single demand node, which has water supplied internally by the rainwater tank and externally by the desalination plant node and two reservoir nodes (Myponga and combined HV and MB). The reservoirs have associated catchments, which use a calibrated WC1 catchment runoff model (Cresswell *et al.*, 2002) to determine appropriate catchment runoff. The final supply node is the River Murray supply, which supplies water to the combined HV and MB reservoir.

4. RESULTS

The results of the scenarios are presented in Table 2 and are subsequently discussed in terms of their economic cost, GHG emissions, reliability, resilience and vulnerability. Finally, the trade-offs between supply types are evaluated and the resulting management implications for the Southern System are discussed.

Table 2: The risk based performance indicators, economic cost and GHG emissions for each of the scenarios developed for Adelaide's Southern water supply system

Scenario	Size of Desalination Plant (ML/day)	Size of Rainwater Tank (KL)	River Murray Licence (maximum supply) (GL/yr)	Cost ($2007 billion)	GHG emissions (millions of tonnes of CO_2-e)	Reliability	Resilience (years^{-1})	Vulnerability (GL)
Base	150	0	65	$ 3.41	15.1	90%	0.80	18.33
1	75	0	65	$ 2.01	10.3	62%	0.55	45.44
2	300	0	65	$ 6.22	24.9	100%	∞	0.00
3	150	0	32.5	$ 3.37	14.5	37%	0.33	50.83
4	150	0	80	$ 3.41	15.2	94%	1.00	3.33
5	150	5	65	$ 5.40	15.8	94%	1.00	3.53
6	150	15	65	$ 6.37	17.4	98%	1.00	3.13
7	150	30	65	$ 7.84	19.0	98%	1.00	3.13

4.1. Economic cost

When the size of the desalination plant and size of the rainwater tanks are altered, the economic cost for the total system changes dramatically; there is a $4.2 billion difference between the 75 and 300ML/day desalination plant scenarios and a $4.4 billion difference between scenarios with no rainwater tanks and 30KL rainwater tanks (Table 2). Contrastingly, the additional economic cost when the River Murray licence is altered from 32.5 to 80 GL/yr is only $40 million (Table 2). This is because the costs per KL for desalinated water (150ML/day plant) and rainwater (5KL tanks) are approximately $1.15/KL and $4.05/KL, respectively, which is much higher than 20c/KL, the current price for River Murray water. This indicates that the cheapest method of increasing water supply in the Southern system is to buy River Murray licences. However, if water availability in the River Murray is reduced in the future and licences cannot be bought, then in order to meet the Southern system demand, costs will significantly increase. Increasing the size of the desalination plant from 150ML/day to 300ML/day will increase costs by $2.8 billion, higher than the $2.0 billion it would cost to install 5KL rainwater tanks (Table 2). However, in this scenario, 55GL/year of additional water would be supplied by the desalination plant, compared to an average contribution of 13GL/year from all of the 5KL rainwater tanks. Therefore, following River Murray supply, desalinated water is the next most cost effective solution to increasing water supply for the Southern system.

4.2. GHG emissions

Table 2 illustrates that the size of the desalination plant greatly influences the total GHG emissions of the Southern system, with a change of 14.6 million tonnes of carbon dioxide equivalents (CO_2-e) between the 75 and 300ML/day plant scenarios. Table 2 shows that the size of the rainwater tanks has a smaller influence on total GHG emissions (a range of 3.9 million tonnes of CO_2-e), while the influence of the River Murray licence is smaller still (a range of 0.7 million tonnes of CO_2-e). This occurs because a 150ML/day desalination plant produces approximately 5.6kgCO_2-e/KL, a 5KL rainwater tank produces approximately 2.5kgCO_2-e/KL and the River Murray currently produces approximately 1.7kgCO_2-e/KL. This indicates that to simultaneously increase supply but keep GHG emissions low, buying more River Murray licences should be the first option, followed by installing rainwater tanks and then by increasing the size of the desalination plant.

4.3. Reliability, Resilience and Vulnerability (Risk Based Performance Assessment)

As Table 2 indicates, the system's risk based performance was significantly improved with increases in the size of the desalination plant; reliability ranges from 62 to 100% (the system fails between 20 out of the 52 years and zero years), resilience ranges from 0.55 per year to ∞ (when failure occurs, the system fails on average for approximately two years or the system does not fail) and vulnerability ranges between zero and 45GL (the average shortfall is between zero and 32% of the 140GL/yr demand). Changes to the River Murray licence resulted in slightly greater changes to system performance; failures could occur in three years (reliability of 94%) or up to 33 of the 52 years (reliability of 37%), if failures occurred they would take place for a year or up to three consecutive years (resilience of 1.0 and 0.3, respectively) and the system could have a shortfall of between 2% and 36% of the Southern system demand (vulnerability of between 3 and 51GL) (Table 2).

Increasing the size of household rainwater tanks from 0 to 5KL reduced the number of failure years from five to three (reliability ranges from 90 to 94%), reduced failure length from one and a quarter years to only one year (resilience ranges from 0.8 to 1.0) and reduced the system shortfall by 15GL (vulnerability decreases from 18 to 3GL) (Table 2). However, Table 2 also shows that increasing the rainwater tank size from 5 to 15KL only slightly improves system performance; the number of failure years decreases from three to one (reliability increases from 94% to 98%), average length of failure is still one year (resilience is constant at 1.0) and there is only a 400ML difference in system shortfall (vulnerability decreases from 3.5 to 3.1GL). Finally, doubling the 15KL rainwater tank to 30KL does not influence system performance (Table 2). These results occur because as rainwater tank size increases, the amount of additional water that the rainwater tank can contribute to the system decreases. For example, in an average year a 5KL rainwater tank can provide 34KL, whereas a 15KL tank can only provide an additional 10KL of water per year despite being three times the volume. This occurs because regardless of rainwater tank size, the tank regularly runs out of water during summer (due to low rainfall), so the only opportunity the larger tank has of contributing more water to the system is during winter. Thus, during summer, water supply for the Southern system must be primarily sourced from the other supply sources.

These results highlight the necessity of either a large desalination plant or a large River Murray licence (or a combination of both) to ensure that supply meets the demand of Adelaide's Southern system. Furthermore, they indicate that the installation of small household rainwater tanks would reduce the vulnerability significantly, whereas installing larger rainwater tanks would have a negligible effect on further decreasing the vulnerability of the system. Consequently, small rainwater tanks should be a potential management option for improving system vulnerability, but as they still leave the Southern system without a reliable water source in the summer months, they should be used in conjunction with a large desalination plant and/or additional River Murray licences.

4.4. Trade-offs between supply types and management implications for the Southern System

The results clearly indicate that trade-offs exist between economic cost, GHG emissions and risk based performance for the supply types of the Southern System. Increasing the River Murray licence improves the technical performance of the system and keeps both economic cost and GHG emissions low, whereas increasing the size of the desalination plant improves the technical performance of the system and keeps costs relatively low, but increases GHG emissions of the system dramatically. Contrastingly, installing 5KL rainwater tanks improves system performance, keeps GHG emissions relatively low but is associated with a large increase in system cost for the additional water supplied. Furthermore, rainwater tanks larger than 5KL are not likely to be effective in significantly increasing the system's risk based performance.

Therefore, in terms of all three sustainability aspects, additional water required in the future should initially come from the River Murray. However, because of the uncertainty surrounding River Murray licences in the long-term, a desalination plant and household rainwater tanks should also be considered. Because of the trade-offs between these two supply types a combination of both is favourable. For example, one potential solution could include installing small rainwater tanks in every household and building an appropriately sized desalination plant.

5. CONCLUSIONS AND FUTURE DIRECTIONS

This study indicates that supply from the River Murray is preferable to a desalination plant and rainwater tanks in terms of the economic cost, GHG emissions and technical performance of the system. However, uncertainty over future River Murray licences requires a desalination plant and rainwater tanks to be considered as feasible water sources. Desalinated water is preferable to rainwater in terms of economic cost, but this is reversed when considering GHG emissions. In terms of technical performance, small rainwater tanks are beneficial but must be used in conjunction with other water sources because of their high dependence on rainfall. Therefore, if River Murray supply is unavailable, a combination of small rainwater tanks used for garden watering and toilet flushing (around 5KL capacity) and a desalination plant would be appropriate for the Southern system.

Future directions for research in this field include:

- Developing a multi-objective optimisation component to illustrate the optimal trade-offs in sustainability aspects across the range of supply types in order to identify a set of optimal sustainable solutions,

- Incorporating other alternative supply types, such as stormwater reuse,
- Expanding the environmental dimension, for example incorporating brine disposal and river health, and
- Conducting detailed sensitivity analyses to assess the uncertainty in modelling the future scenarios.

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