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# A Dynamic Water Supply Portfolio Optimisation Approach

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**Abstract:** This paper examines the future water supply situation in Adelaide, a relatively dry city in South Australia, in the driest populated continent on earth. Using the Systems Approach, we analyse a diversified strategy with a new portfolio mix of core bulk water: (i) rainfall independent desalinated water from the ocean and (ii) rainfall dependent water from catchments including the Mount Lofty Ranges (MLR) and water piped from the Murray-Darling Basin (MDB) including via the Mannum-Adelaide Pipeline. Our focus is on the quantity, indicative costs and risks of water supply, and associated augmentation choices and trade- offs, over the next century to 2114. We model using historically-based projections of drought risks and growth pressures, reflecting a century of rainfall and catchment inflow data based on historical data obtained from Australian Bureau of Meteorology and SA Water, water services in South Australia. A major finding through our simulations is that demand more than drought is the real and looming source of long term shortages of supply relative to demand. However, short-term risks differ depending on the composition of the supply portfolio. Expanding dams and pipelines will allow a greater share of MDB water to be accessed, but at substantial drought and political risk. Over the next 100 years demand may nearly treble, but the water volumes and the battles over sharing MDB water, dams and pipelines may remain the same. Thus, it is the gap between demand and supply that, absent desalination plants, will generate increasing water supply crises in Adelaide and elsewhere.

***Keywords**:* Water security, water supply portfolio optimisation, system dynamics modelling, drought mitigation.

## 1 INTRODUCTION

The Murray-Darling Basin (MDB) in south-east Australia is characterised by a high degree of climatic variability and extreme weather events such as floods and droughts. The 'Millennium Drought' in South Australia between 1997 and 2009 was the worst drought in recorded history across the MDB with average rainfall 12.4% below that for the 20th Century, resulting in widespread environmental and socioeconomic impacts (Pink, 2012; van Dijk et al., 2013).

Adelaide, the capital of South Australia (SA), reflects the water supply pressures and threats facing a growing Australian city with modest rainfall and a resulting dependence on the River Murray, sourced from three other states (Victoria, New South Wales, and Queensland). With the smallest local storage capacity relative to demand of all capital cities in Australia, sufficient for just one year's annual demand of 200GL (Borchardt, 2012), an average of 60% of Adelaide's total supply is derived from reservoirs dependent on the Mount Lofty Ranges, with the remaining supply piped from the River Murray. The relatively large reserves of water in the MDB and the relatively modest cost of pipelines and transfer dams, made a strong case for a piped connection to the River Murray. While past supplies from the River Murray have met an average 40% of Adelaide's water supply, demand is growing with population and varies significantly, reaching 90% in 2008 in the Millennium Drought (Porter et al., 2015). Thus despite being a climate dependent source itself, the River Murray has provided Adelaide, not only base load supply in average rainfall years, but water security in dry years. Thus, Adelaide cannot rely on accumulated storages as inflows declined and rather, a higher proportion of supply had to be extracted from in the future, and particularly if aggravated by drought. To address this issue, the SA government decided to construct a rain-independent desalination plant with investment of AU$1,824 million in 2008, capable of supplying 50% of Adelaide's annual demand.

In this paper, we present a portfolio approach suggesting a mixed strategy of desalination and water trading to meet growing demand over the hundred year period from 2014. Considering that desalination is now part of the mix of bulk water supply, we explore the options from management of a diversified portfolio of core bulk water under differing scenarios regarding supply (rainfall, piped water and desalinated water) and demand (population growth and environmental flow policies) and consequently differing risk-cost trade-offs between supply sources.

## 2 APPROACH

Water resources systems are characterised by multiple interdependent components that together produce multiple economic, environmental, ecological and social impacts (Loucks and van Beek, 2005). Thus, actual or feared loss of safe and secure water supply can have unfathomable costs and consequences, making design of management and use networks a priority for systems of governance. Water utilities working to improve performance of these complex systems must identify and evaluate alternative supply design and management strategies knowing the uncertainties in future projections of supply and demand given the vagaries of rainfall and climate variability. For example, a damaging drought, or flooding, can come in many different magnitudes and duration, and may be devastating if they are not managed well. Plans can be made to mitigate the consequences of shortfalls, requiring foresight, initiative and flexibility of systems use in order to cover changing conditions. Simulation modelling in advance is an effective method for evaluating the management of regional or citywide water supply systems as well as exploring the interrelated impacts of various supply and demand and options that are being used now or considered in the future (Sahin et al., 2015; Sahin et al., 2016).

### 2.1 Systems Approach

The System Dynamics modelling (SDM) used in this study provides a robust platform for analysing the interactions between variables influencing water demand and supply, and for exploring the sensitivity of results to economic, social and environmental assumptions. SDM is a powerful tool for informing policy-makers seeking to evaluate long term planning of water supply options including augmentation decisions. A strength of this modelling approach is that the sensitivity of the model to the baseline assumptions can be explored. In our case we can evaluate desalination plant size, timing, trigger levels for desalination operating rules, and critical dam levels that influence desalination investment decisions. Further, this modelling approach facilitates sensitivity analysis that informs the nature and scale of water investment decisions, be they dams, desalination or importation and sale of water in the short or long run. SDM was first developed for desalination and applied in South East Queensland, Australia to explore scarcity pricing (Sahin et al., 2015) analysing the potential for pressure retarded osmosis (PRO) technology to generate electricity (Sahin et al., 2016). This model was subsequently modified for Melbourne (Porter et al., 2014; Scarborough et al., 2015) to explore rain independent desalination versus more traditional rain dependent dams in long term planning. Further details of the model can be found in these papers (Porter et al., 2014; Sahin et al., 2015; Scarborough et al., 2015; Sahin et al., 2016). Based on these previous studies, the generalised model has been customised for optimising the water supply portfolio in Adelaide. In this context, the SDM, using the Vensim® DSS (Ventana Systems, 2012), was built by identifying key variables, estimating assumed relationships between these variables and finally parameterising these relationships. In building the SDM, a participatory modelling approach was employed. Participatory model development can focus on portraying system structure, while model simulations reveal system behaviour, which is less intuitive and often a source of confusion (Vennix et al., 1996; Van den Belt et al., 2004; Langsdale et al., 2007).

### 2.1 System Boundary and Key Assumptions

System boundaries are important in identifying the key model input variables as well as in assessing their interdependencies. Key variables required were identified through a comprehensive literature review, expert consultations, and workshops with experts, water utilities and researchers (Table 1).

Table 1: System boundary and baseline assumptions for Adelaide's water system

| Variable | Baseline Assumption |
|---|---|
| Population - current[1] | 1.29 million |
| Population growth rate (%)[2] | Varying from 0.5% to 1.5%, Default = 1.2% |
| Current water use (per capita)[3] | 340 (Litres/person-day) (residential and non-residential) |
| Dam capacity (current)[4] | 200 GL |
| Desalination capacity (current)[4] | 100 GL/year |
| Water entitlement[4] | Default 650 GL/5 years |
| Desalination capital costs[5] | Varying from AU$1-3billion Default = AU$ 1.2billion |
| New dam capital cost[5] | $A1.7 billion (100 GL dam) |
| Desalination operating cost[6] | $A1.0/kL + $30 million (Depending on water order) |
| Dam operation costs[6] | $A0.24/kL – Water from Mount Lofty Ranges<br>$A0.44/kL – Water from River Murray<br>$A0.36/kL – Ground water |
| Size of new desalination plant[5] | Varying from 50 to 150 GL/year - Default = 50 |
| Size of new dam[5] | Varying from 50 to 150 GL - Default = 100 GL |
| Capital cost of new pipeline | $A300 million (for 100 GL/year capacity) |
| Market price of water | Varying $A0.50-$A 2.50/kL |
| Model time bound | 100 year |
| Time interval of simulation | 1 year |
| Water storage to demand ratio | Varying 1 to 1.25 |
| Social discount rate[5] | 1.5% |

*Australian dollars (0.9685 USD = 1.0 AUD average for 2013 prices

[1] ABS (2014)
[2] ABS (2013)
[3] Porter et al. (2015)
[4] Productivity Commission ( 2011)
[5] Scarborough et al. (2015)
[6] Marchi et al. (2014)

A flexible rather than fixed scenario approach was employed: we built a model with scope for expanding modular units of desalination and dam capacity when justified, and with average costs stabilised through trading MDB or river water, except where prevented by drought or cost.

## 3 RESULTS

We simulate inflows from the Mount Lofty Ranges (MLR) and government-assigned allocations over the 100 years from 2014 based on rainfall data for North Adelaide from 1900 (Bureau of Meteorology 2013) and recent data on actual River Murray extractions (1984-2013) provided by SA Water. We do not pretend to forecast a century ahead; rather we apply the rainfall patterns and droughts of the past to estimates of probable populations and rainfall variability of the future, to indicate the supply mix and cost alternatives of varying outcomes given demand growth and supply assumptions. To derive these simulations we first generate random data on future rainfall levels using the historical data, making some adjustments for our alternative drought scenarios. We then estimate the relationship between inflows to the MLR and rainfall levels. The estimated coefficients are used to simulate future inflows from the MLR and to estimate future water allocations from the River Murray against entitlements.

### 3.1 Drought Conditions: Water Supply and Demand

In the SDM, a shortfall in water supply (as observed in 2008), and an associated need to purchase allocations in the market, is defined to occur when the sum of ground water, water supply from the Mount Lofty Ranges and Adelaide's government assigned allocation from the River Murray are insufficient to meet projected demand. Then, the volumes and costs of a mix of desalination and the flows from the market topping-up those water supply shortfalls are assessed, enabling a comparison with a pre-desalination situation. The results in Figure 1 suggest that either (i) there would be greatly expanded use of MDB water trading, possibly requiring duplication or expansion of pipelines from the Murray to Adelaide dams (Figure 1a); or (ii) SA Water would build a second desalination plant around year 33 followed by a third in year 60 (Figure1b). Existing catchment and MDB allocations including the current desalination plant indicate a need for augmentation through purchases or extra desalination capacity. The desalination response scenario (Figure 1b) sees Adelaide growing to three 100 GL/pa desalination plants (including the current desalination) in the context of very little water trading (the red bars Figure 1b relative to a single desalination plant in Figure 1a).

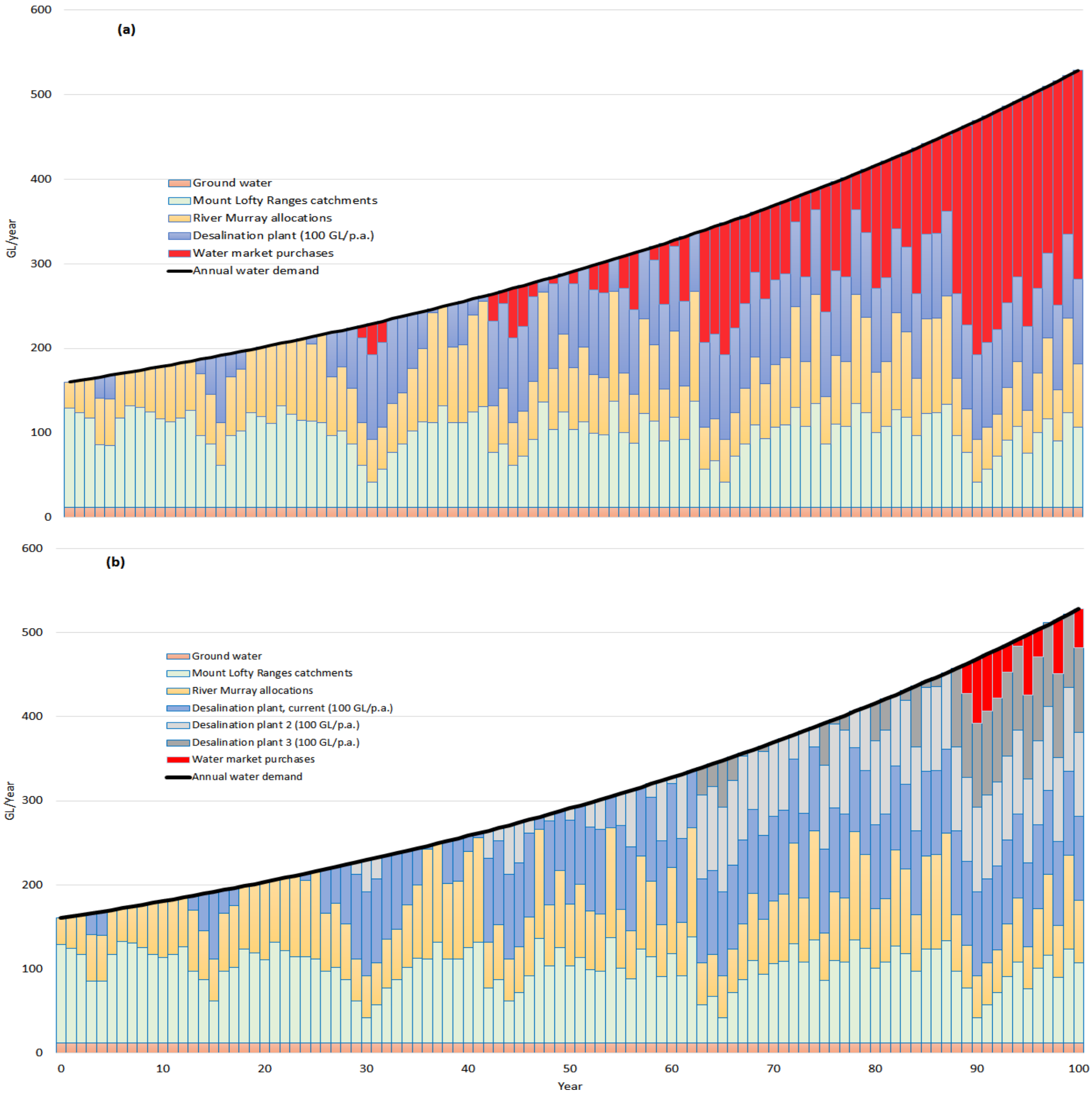


Figure 1: Supply and Demand over the next 100 years with five mild droughts: (a) no new investments, (b) 3 new desalination plants, and entitlement 650 GL over five years

### 3.2 Cost Analysis

While existing dams and catchments will initially cover normal base load demand, as the century progresses population based demand is assumed to necessitate more traded or desalinated alternatives. Trading prices during recent periods (including shorter term water storage costs) have varied between $0.50 (normal) to $2.50/kL (drought) based on rainfall level (Figure 2). While the average unit cost of reverse osmosis desalination has fallen significantly over the last two decades, the costs of desalinated water in our models are higher at $1.0/kL (plus a $30 million per 100 GL/year desalination plant standby capacity charge) than MDB or MLR water. These global cost levels for desalination, due to reverse osmosis, have however fallen significantly over the last two decades. The prices of purchased river water will most likely be far higher in future droughts than we have assumed as demand pressures and supply constraints operate. Figure 2 shows the costs of a supply mix to meet growth in demand over the century based on rainfall projections. The variation and level of *marginal* costs with additional desalination plants is significantly less than when dependent on trading from the MDB, making desalination a more secure and cost effective future means of expanding supply in a drought if not the lowest cost over the whole rainfall cycle.

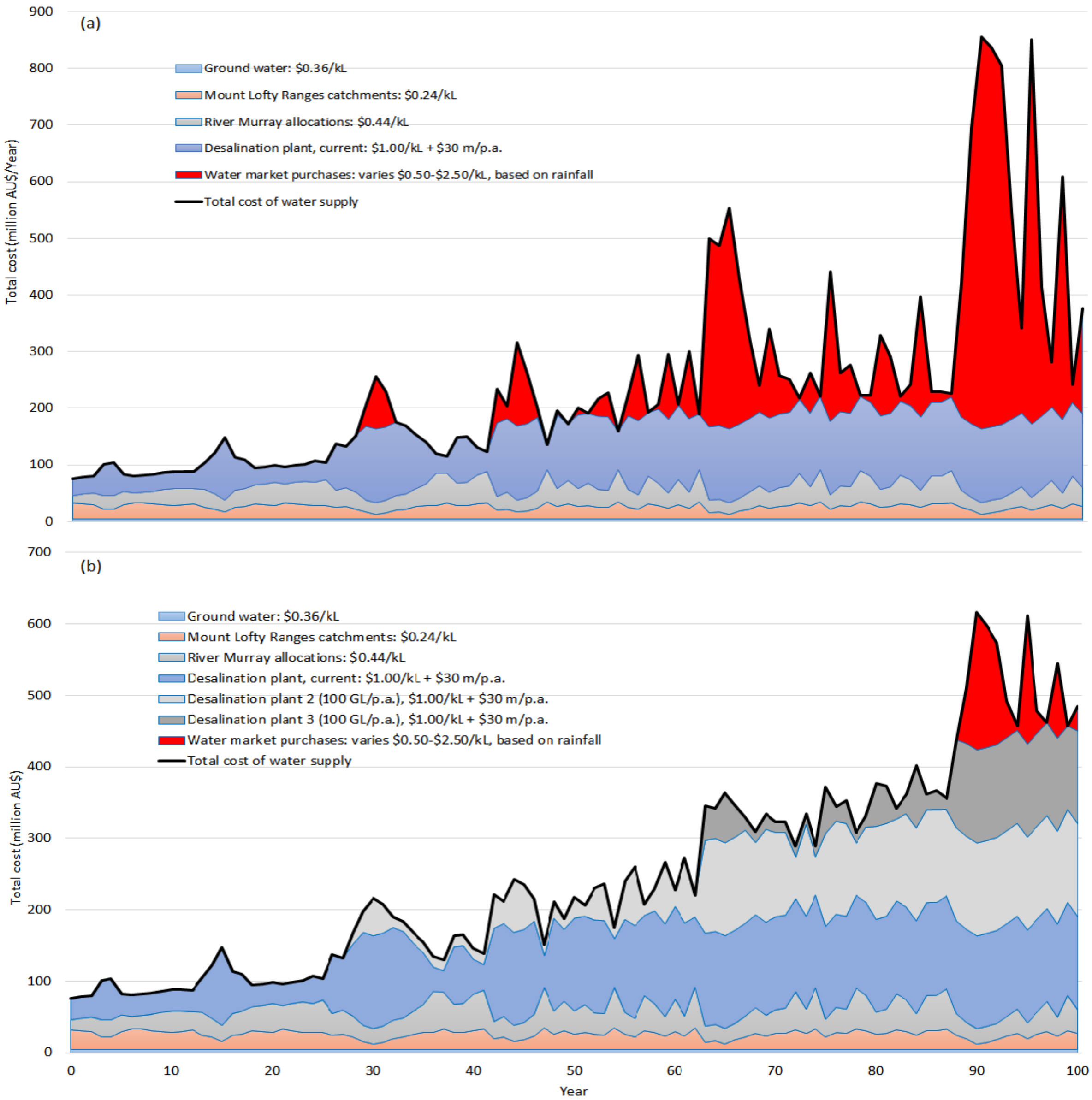


Figure 2: Simulated total operating costs by source, 2014-2114: (a) No new desalination plants); and (b) Two new desalination plants

As shown in the Figure 2, the major value in desalination investment comes initially from dampening swings in costs and removing restrictions and later as base load supply, in response to the almost doubling of total demand. There is also the benefit of expanding short term supply in a drought, adding only the costs of activation of the plant currently on standby. Thus, the desalination plant serves as insurance preventing escalation of traded water prices during droughts and avoiding the need for water restrictions.

### 3.3 The Cost-Risk Trade-Off: Desalination versus Water Trade

Figure 3 shows the estimates of the operating costs of an either-or supply scenario in relation to desalination and water trading. The blue area plots the five-year rolling average operating costs for Security Level 1 (ratio of capacity to annual demand) when Adelaide meets demand through purchased allocations from the MDB, with desalination on standby. The purple dots show timing of dam and pipeline expansion costs. The red bars project costs when extra water is sourced solely from desalination, a line that rises as the second, third and fourth 50 GL/year desalination plants come on line (as indicated by the green dots). While desalination operating costs per kL are higher on average than pumped and treated river water, this is not true when drought hits, and purchasing water costs far more per kL. (In this research, the past rainfall- trading price was used to estimate costs from purchasing water). It should be noted that Figure 3 almost certainly understates the emerging future real costs of purchasing water (blue area in the Figure 3), as river water will become increasingly scarce and pricier than indicated by past relationships, due to population and economic growth. Figure 3 also highlights that for Adelaide, the modelled operating cost of desalinated water is generally higher than from purchasing via the MDB - i.e. from greater allocation trading. What the availability of desalinated water does is avoid the peak costs during drought, making average water portfolio costs more stable and predictable. In addition, in the absence of desalination, the spikes in costs during drought would almost certainly flag a return to costly and inconvenient water restrictions.

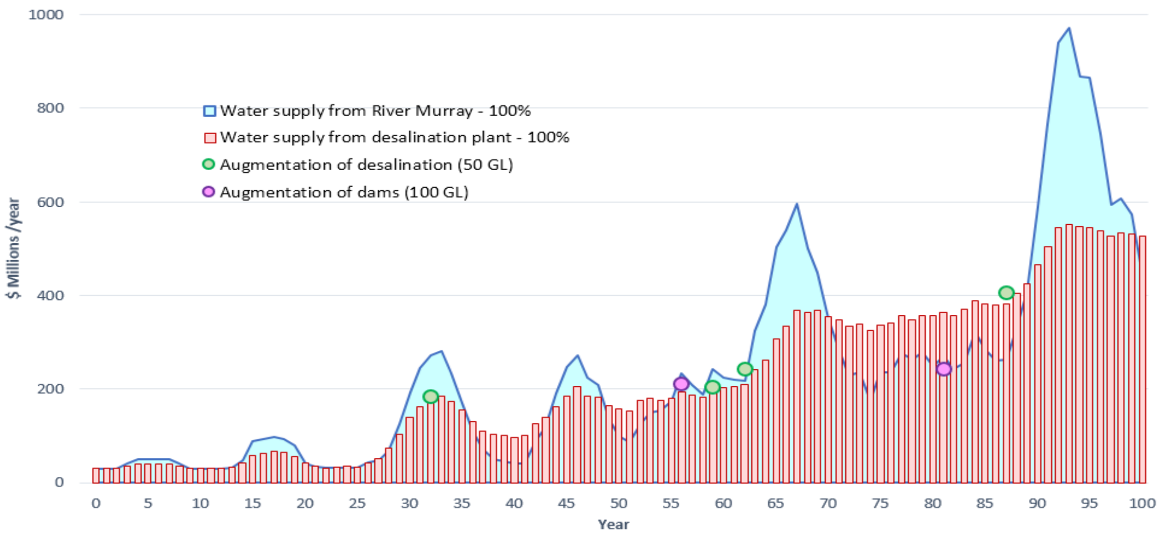


Figure 3: Total Operating Costs, Desalination or Market Trade, 2014 - 2114 (5-year moving average, constant 2014 prices)

### 3.4 Funding the Water Supply Mix: A Comparison of Augmentation Investments

Expanding supply solely through market purchasing of MDB entitlements and allocations to meet additional demand also requires augmentation of Adelaide's modest 200GL capacity; i.e. new dam and pipeline capacity to store and pump water from other catchments, principally via River Murray. Alternatively, a pure desalination strategy requires further desalination plants. Figure 4 compares the full augmentation costs (capital and operating) of the additional dams/pipelines or desalination plants to provide an additional 230 GL capacity or flow, discounted up to the year in question.

Desalination and allocations are both flow sources of water supply, with the latter in the case of the MDB having greater cost and volume uncertainty, while also eventually requiring expanded dams/pipeline expansion to increase storage capacity. While investment in desalination flow capacity does not expand storage capacity, it can optimise existing capacity and provide unconditional water flow independent of rainfall. Figure 3 presents the comparison of required augmentation costs using a 1.5% real discount rate. The augmentation cost of dams include investment, operating, maintenance and other capital costs of a new pipeline. Additionally, in Adelaide's case, if water in excess of current "free" entitlements of 650 GL over 5 years is sourced from water trading, the total cost of water provided through dams includes additional cost of MDB market purchases.

When we add capital and operating costs of restoring water security in Adelaide through expanded dams and desalination, and allow for timing and modularity factors, it turns out desalination will have lower discounted costs – estimated at $4.6 billion at a real discount rate of 1.5% in contrast to $4.9 billion for expanding use of river water at a security level of 1.00, or over $7.2 billion should dam and pipeline capacity be expanded so Adelaide has a more acceptable (but still the lowest) storage/demand security ratio of 1.25.

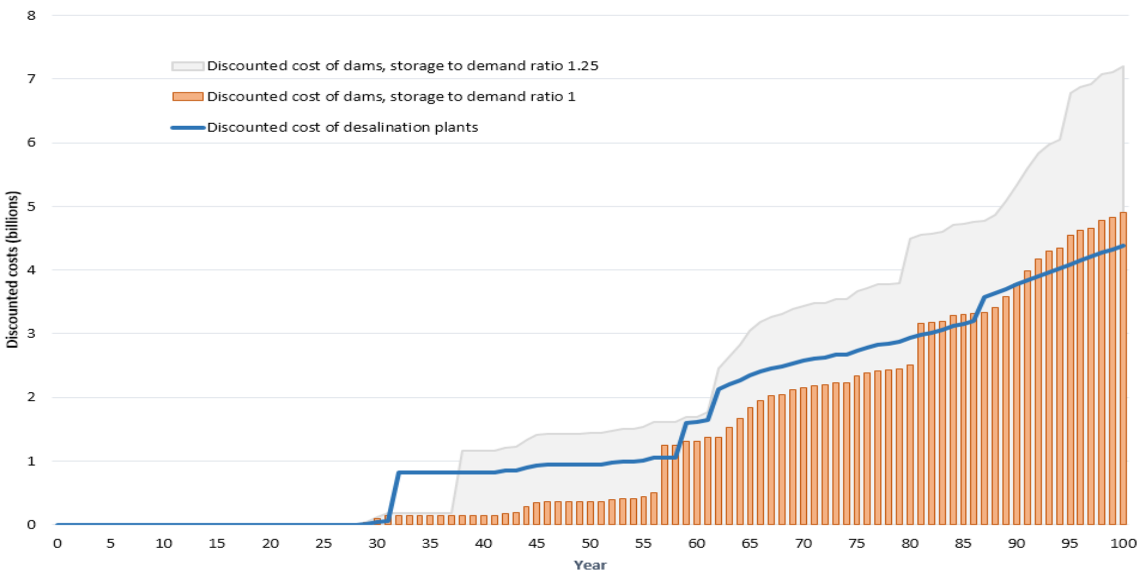


Figure 4. Discounted Capital and Operating Cost of Supply Augmentation, Desalination or Dams, at differing security levels (Social discount rate of 1.5 %)

As shown in Figure 4, for a security level (capacity/demand) of only 1, the estimated discounted total costs of expanded water supply, being either the brown bars for 100% river water, where the water purchase or market trading strategy includes new dams, new pipeline and market purchases, or the blue line using expanding modules of desalination plants. The grey area indicates the sharply higher capital and operating costs of raising security (storage to annual demand ratio) to 1.25, causing an estimated $2.6 billion higher discounted cost relative to desalination and about $2.3 billion margin relative to the lower current security level 1.

## 4 CONCLUSION

This paper has assessed the role of desalination in metropolitan Adelaide bulk water portfolios in the next 100 years, in the context of the last 113 years of rainfall data, desalination, dams and pipeline costs. Our simulations show that in the absence of new desalination capacity by the middle of the century, Adelaide will face political risks re access to MDB water, meaning uncertain but escalating costs of importing water should that be agreeable to the eastern states and, probable long term water restrictions and threatened water-intensive gardens, sports fields, parks and industries. This is all due to a combination of likely growth in population and the economy in and around Adelaide plus ongoing rainfall patterns. Absent new desalination capacity, Adelaide water supply will increasingly require augmentation through external river purchases about double their current level – assuming a willingness to sell allocations or entitlements from the MDB.

Our simulations, reflecting demand projections and 113 years of rainfall data, suggest that absent desalination expansion, the need will be for dramatically increasing imports of Murray-Darling Basin water, growing to 200GL by 2114, and at increasingly expensive and uncertain prices. Water transfers to SA, despite agreements, and increasing water restrictions. The alternative is a sequence of four demand-driven 50 GL units, generating total of 300 GL of desalination capacity over the hundred year period. More likely than the either/or strategy for MDB pumped or desalinated water, is an expanded mix of traded water from the MDB and a sequence of desalination plants with predictable costs. Such a mixed strategy will moderate periodic spikes in MDB water purchase prices, and reduce the need for, or enable abolition of water restrictions.

The SDM in this research uses more than a century of historical rainfall data for Adelaide and the MDB and assumes current rates of growth of the economy and population. The resulting trade-offs are characteristic of the application of efficient systems dynamic applications combined with portfolio theory. The desalination framework illustrates how economic development may no longer be blocked by water scarcity, climate change or drought, but may face costs of reverse osmosis including energy costs that should be less than for expanding dams. While most of the time the future and moderate low average cost of water supply will reflect lower source costs in the Mount Lofty Ranges' catchments and the

Mannum Adelaide pipeline for example, security in long-term water supply will come from the rainfall-independent supply sourced from oceans.

One major uncertainty clearly relates to the energy cost component of reverse osmosis. In Adelaide as for other desalination plants governments have tended to make energy costs higher than necessary in the grid, because of environmental pressures to use renewable sources. Regardless of facts or politics, and plausible cost revisions, our cost analysis shows that economic and population growth means desalination should be an integral part of Adelaide's efficient bulk water portfolio as the century unfolds, as land for catchments and dams become relatively more expensive and risky, and as drought uncertainties make essential water trading vulnerable to drought, unlike desalination.

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