Melbourne School of Engineering
Department of Infrastructure Engineering

The economic value of water in storage

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Project Team

The University of Melbourne Project team consisted of:

- Professor Andrew Western, Infrastructure Engineering, University of Melbourne;
- Professor John Langford, Steering Committee Chair, University of Melbourne; and
- Research Fellow, Nathan Taylor, University of Melbourne.

Steering Committee

The project was informed by the members of the Steering Committee consisting of:

- Richard Smith; Business Planning and Regulation Manager; City West Water;
- Udaya Kularathna; Team Leader Water Resource Assessment, Integrated Planning; Melbourne Water;
- Bruce Rhodes, Manager Water Resources Management, Melbourne Water;
- Ian Johnson; Manager Urban Water Policy; South East Water;
- Dominic Keary; ESC Project Manager; Yarra Valley Water; and
- Stephen, Sonnenberg, Manager Urban Water Security Policy, Department of Environment, Land, Water & Planning.

The Steering Committee was Chaired by Professor John Langford, University of Melbourne. While this report was informed by the Steering Committee, the findings contained in the report are the responsibility of the Project Team and not the Steering Committee or the organisations they represent.

Key findings

- Maintaining water security objectives for customers requires complex decisions to be made within a complex operating environment. The outcomes are driven by current strategies, policies, system configurations, and operating arrangements guided by the best information and past practices.
- The modelling techniques developed in this report provide valuable economic information underpinned by rigorous analysis of hydrologic variability to assist those policy, planning, augmentation and operation decisions for complex real-world water supply systems.
- Armed with these new tools, the capacity exists for decision makers to further test critical decisions, short and long term, to improve economic outcomes for the State and water users.
- Traditionally, the "costs" taken into account for decision making included the "engineering" costs associated with augmenting the system (sources and / or grid infrastructure) based on typical streamflow conditions, the costs of making desalinated water orders and system pumping costs.
- This report, and the models it has developed, also include the costs to society of not being able to supply water to meet demands, the opportunity costs associated with water trading, and the impact of variations in the timing of augmentations related to variations in water availability.
- A further critical factor is the current policy(ies), existing infrastructure and operational arrangements. Understanding these "current" costs as a base, then allows examination of:
  - How altering policies and operating arrangements could impact (positively or negatively) the expected costs of maintaining water security; and
  - Evaluating future options to maintain water security to determine the least cost approach, for a given set of hydrological assumptions.
- With respect to the current policies and arrangements, the modelling is very clear that holding additional water in storage has significant economic value as it reduces the need to expand the water supply system and / or delays it. This is because Melbourne has large reservoirs relative to inflows. It also reduces the expected economic and social costs of restrictions.
  - This water could come from additional usage of desalination, water trading, demand management or other integrated water management options, each with varying worth.
  - Substantial reductions in the costs of supplying water over the long term are achieved by using desalination at consistently higher rates than current operating policy. This further reduces the risk of very low storages in severe drought and early expansion of the water supply system. That is the desalination plant is better used to provide a buffer of stored water than as a last-ditch insurance policy. These benefits would reduce the costs of supplying water to Melbourne by $47.5 million, or 14.8 per cent of the expected costs for a 70 per cent initial storage.
- It was also found that:
  - Reducing the delivery time for water supply system expansions that may be needed to avoid storages falling to very low levels in times of critical shortage delivers substantial economic benefits by ensuring those expansions happen less often is delayed.
  - Early planning and other measures to reduce the delivery time of emergency water supply expansions is therefore crucial and could reduce the cost of supplying water by $104 million, or 32 per cent, of the expected costs for a 70 per cent initial storage.
- The possible savings identified in this report refer to those incurred in delivering a reliable water supply over twenty years. The operating costs of pumping and purchasing water are considered in this report, but operating costs that are common to all options are not. The incremental costs of reliability should be explicitly incorporated in decisions involving the operation and management of the water supply system.
- There are "costs" in maintaining policy and operational positions and the modelling provides the opportunity to value additional benefits of policy changes that could result in improved outcomes.

Executive Summary

As Australia has a notoriously uncertain climate this report sets out a methodology to establish the economic value of water in storage. This can inform trading, operation, and augmentation decisions. It is possible to have a robust quantification of the value of water in storage given the capacity to produce climate independent water supplies, such as the existing Victorian Desalination Plant, and the capacity to augment these water sources in a relatively short timeframe. The potential augmentations of these water supply sources provide quantifiable costs associated with avoiding water shortages. Having the capacity to generate climate independent water also creates a new opportunity cost for water in storage and defines its economic value. Appreciating the economic value of water in storage can inform decisions about:

- ordering desalinated water, or accessing any other water supply sources;
- water trading - at what price to buy or sell water; and
- the benefits of forward planning of future augmentations.

With the Victorian Desalination Plant, Melbourne's water supply system is now more reliable and can benefit from clearly articulating the trade-offs between risk and the cost of supply as the population it services continues to grow and the climatic conditions remain uncertain. An economically based assessment method is needed as there are explicit costs to access water from the available high reliability sources but only incomplete measures of the benefits. This report sets out a methodology for calculating the expected cost of maintaining a reliable water supply and how this cost changes as storage levels change; thereby defining the value of water in storage. The concepts underpinning the proposed methodology for assessing the Reliability Cost Curve (RCC), and the corresponding value of water in storage, have a long history in hydropower generation. However, they require a few modifications to make them relevant to urban water supplies.

Historically, the opportunity cost of water in storage related to whether it is consumed in this period or at a later date. The trade-off meant that the value of water in storage has been approximated by a comparison between consuming it today versus storing it and consuming it tomorrow. The result is that water authorities have typically harvested stream flows and built large storage reservoirs to accumulate sufficient water holdings to maintain an acceptable reliability of supply during extended droughts. Relying only on restrictions has meant it was difficult to quantify the cost of maintaining reliability in a water supply system as it is difficult to accurately quantify the social losses arising from failing to meet essential for life quantities of demand. While extensive academic research has quantified the social costs of restrictions (see Appendix 1 for a comprehensive review), these studies have not examined the value of maintaining essential for life water supply. Having the ability to deploy reliable climate independent water supply sources provides an alternative means of quantifying short-term risks to the water supply system. Rather than experiencing 'catastrophic' failure to supply, a pre-emptive augmentation may be undertaken.

In Melbourne, water reliability is now underpinned by a range of actions. These include: buying water in the market, using desalinated water, harvesting stormwater, implementing demand management actions, imposing restrictions, augmenting the water supply system or moving water through the grid. To estimate the expected cost associated with delivering a reliable water supply requires a hydrological model of the water supply system, including of uncertain inflows, and an understanding of the current operating arrangements, costs and augmentation triggers. This requires identifying:

1. The costs of operating the desalination plant, the social costs of the restrictions regime, the costs of augmenting the desalination plant and to build additional desalination plants, the costs associated with failing to supply restricted demand and an appropriate interest rate;
2. Creating a model of the Melbourne's water supply system that can simulate the water supply behaviour for a range of initial storage increments, from full to virtually empty, over a medium-term planning horizon;
3. Creating a model that can represent potential supply sources within the context of obligations, operating policies, capacity constraints, price and availability, such as water in the Goulburn system; and
4. Developing stochastic inflow sequences that reflect alternative hydrological assumptions. Two sets of hydrological realisations were generated for this report. The first is based on the Post 75 historic inflows while the second is based on the Post 97 historic inflows. For both sets of hydrological expectations 10,000 twenty-year realisations were generated.

The costs associated with maintaining a reliable water supply are outlined in Chapter 2, while Chapter 3 outlines the model of Melbourne's water supply system, the stochastic inflow generation used, and the estimates of the price for water and its availability, for using the North-South Pipeline. The models used, and the results produced, are included in the attachments of this report.

A base case was examined for both the Post 75 and Post 97 hydrological realisations. To estimate the cost of maintaining a reliable water supply to Melbourne required developing a base case that represents the current operating arrangements and augmentation triggers of the water supply system. The conditions of the base case are outlined in Table 6. While the base case, and subsequent scenarios, were examined under two different hydrological conditions, the results from the Post 97 realisations are presented below, consistent with the current practice for developing Victorian Desalination Plant (VDP) water order advice produced by Melbourne Water Corporation.

Figure 1 shows the various costs included in the analysis. Only those costs directly associated with maintaining reliability over the twenty years modelled are included. It shows that the total expected cost of meeting projected demand in the Post 97 scenario ranges from about $250 million to almost $1,850 million, in net present value terms over that twenty-year timeframe, depending on the initial storage conditions.

The value of water in storage flows from the fact that it helps reduce the costs associated with maintaining a reliable water supply. When storages are high, the value of water in storage stems from it helping to defer the operation of the VDP. As storages fall, the value of water in storage and of operating the VDP arise from avoiding the costs incurred with restrictions *and* with augmenting the water supply system. When the water supply system is expanded, the benefit is it that it reduces the likelihood and frequency of reservoir failure, where there is insufficient water to supply essential for life water to the community. Examining how the RCC changes as current (initial) storage changes provides the economic value of water in storage. The marginal value of water in storage can inform the operation of the system and trading water into, or out of, the Melbourne water supply system. Taking a selection of initial storages, it shows the benefit of having water in storage for a range of specific initial storages.

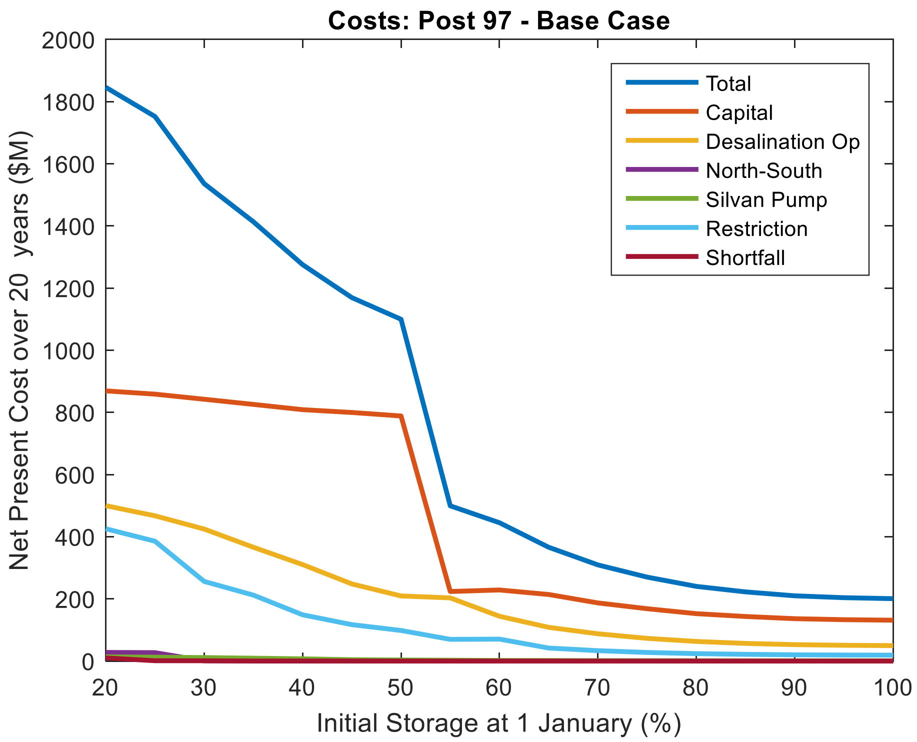

Figure 1: Components of the RCC, Post 97 Base case.

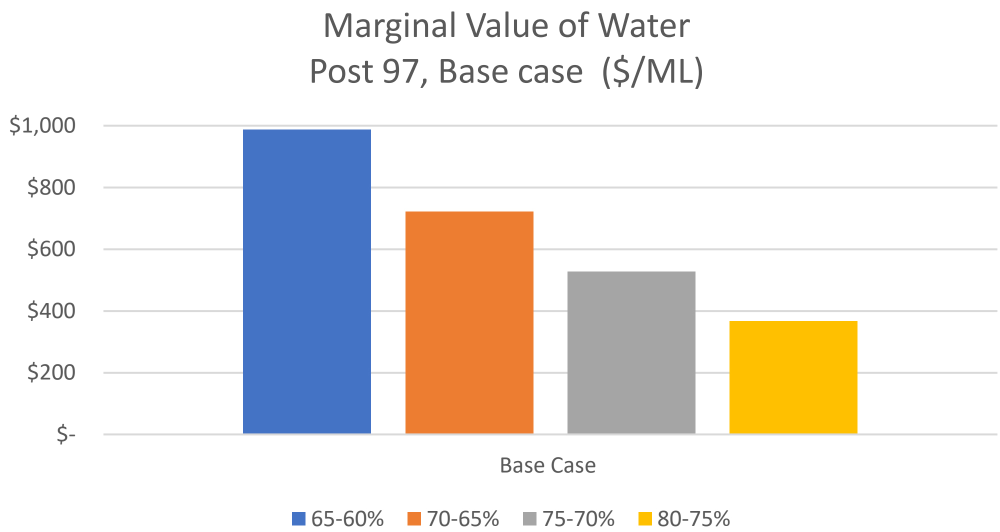

Figure 2: Marginal value of water in storage, Post 97 Base case, selected initial levels of storage.

As Figure 2 shows, the value of additional water varies significantly with the level of water in storage. If storages are at capacity, then additional water has no benefit in terms of supplying water to Melbourne. However, if storages are between 75 and 80 per cent, then additional water is worth almost $400 / ML. If storages are between 60 and 65 per cent, then an additional megalitre of water is worth almost $1,000 as it can help reduce the likelihood and timing of costs associated with supplying water in the future.

Examining how the RCC changes as operational decisions change allows the economic efficiency of these decisions to be evaluated, relative to the base case. A total of four additional scenarios were examined to test the sensitivity of the RCC to operational changes. These include:

1. Changing the operating arrangements of the desalination plant to order at higher initial storages;
2. Changing the operating arrangements of the desalination plant to order at lower initial storages;
3. Altering when water might be accessed through the North-South Pipeline; and
4. Reducing the time it takes to implement a major augmentation in the water supply system, to test preparedness for future climate variability.

Examining the total costs under the alternative scenarios reveals that there are potentially alternative operating arrangements and augmentation programming strategies that can significantly reduce the total expected costs of maintaining a reliable water supply over the twenty-year planning period.

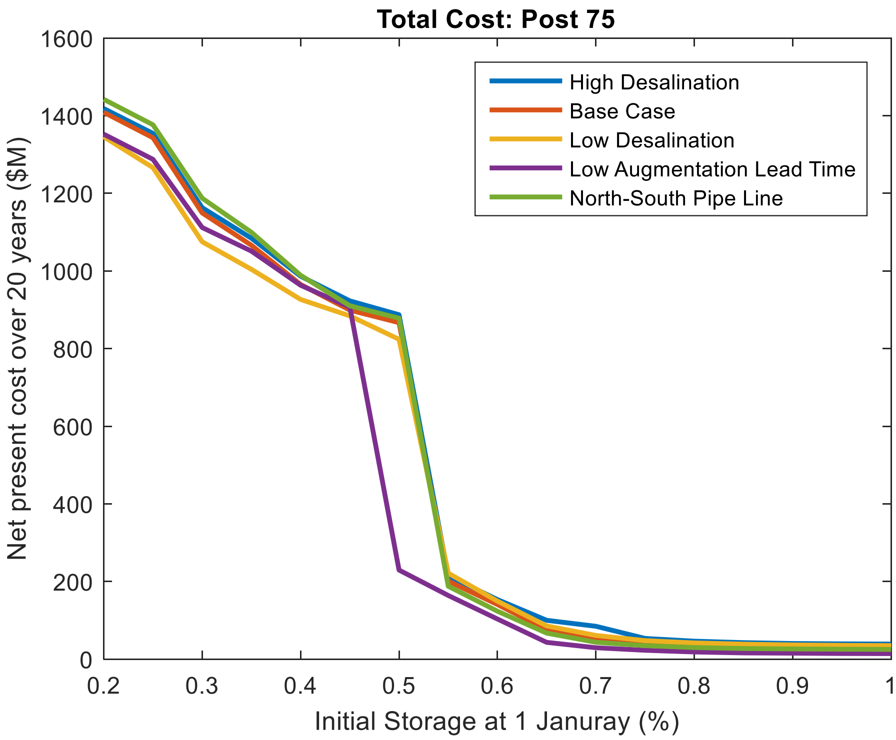

Figure 3: RCC, Post 97, alternative scenarios.

The reason that the total costs of alternative scenarios differ relates to how frequently they incur the costs associated with maintaining a reliable water supply. While Chapter 2 outlines all the costs incorporated, the most critical one is the capital associated with the probability and timing of augmentations to the water supply system. Figure 4 shows how frequently the expansion of the VDP of the water supply system occurs for different levels of storage and different scenarios. By operating the desalination more frequently, this is ordering at a higher storage, you create a greater buffer in the water supply system. As a consequence, the percentage of realisations requiring an augmentation is halved at initial storages above 55 per cent when operating the desalination plant more frequently. Operating the desalination plant less frequently results in more augmentations and thus more cost at all levels of initial storage above 55 per cent.

It should be noted that reducing the length of time required to deliver an augmentation of the water supply system results in the costs associated with maintaining reliability falling. This is because it results in fewer emergency augmentations at every level of storage, because it reduces the storage at which the water supply system needs to be augmented and hence the likelihood of falling below that storage level.

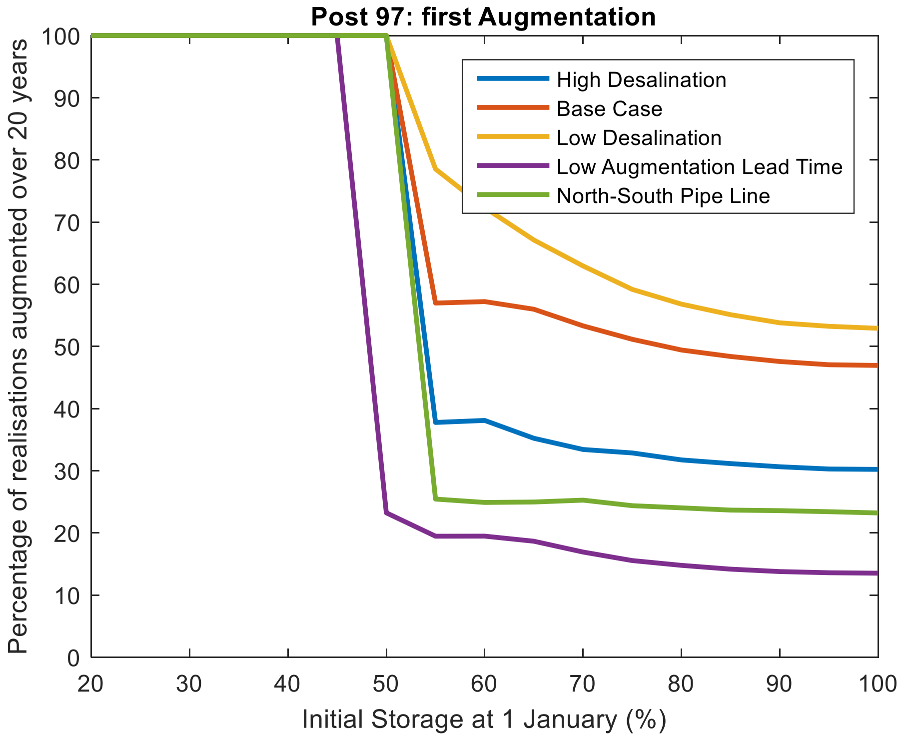

Figure 4: First augmentation of the water supply system, Post 97 Base case, selected initial levels of storage.

Figure 5 shows the cost of maintaining a reliable water supply for various initial storage values. Examining how the reliability cost curve changes, at 60 per cent initial storage, the scenarios examined suggest that the long-run costs of reliably meeting expected demand could be reduced by $59 million, or 12.8 per cent of the long-term costs, by operating the VDP at higher storage levels. It should be noted that this cost reduction refers to the additional costs incurred in delivering volumetric supply reliability (even allowing for the higher desalination operation cost), and that all the other operational costs of the system are excluded, as they are assumed unchanged. Alternatively, by undertaking pre-planning for future augmentations, or possibly revising when water might be accessed from the North-South Pipeline, the expected cost of maintaining a reliable water supply could be reduced by $119 million or $180 million, that is by 25 or 39 per cent. The benefits of alternative scenarios vary based on the initial storage. However, operating the VDP at higher initial storages reduces the expected costs at all levels of storage. While the benefits of alternative scenarios are not cumulative, there may be potential benefits in examining a synergistic set of policies that reduce the expected costs of delivering reliable water.

This study has highlighted that by determining the economic value of water in storage, alternative operational strategies may be considered that provide economic benefits above the base case considerations.

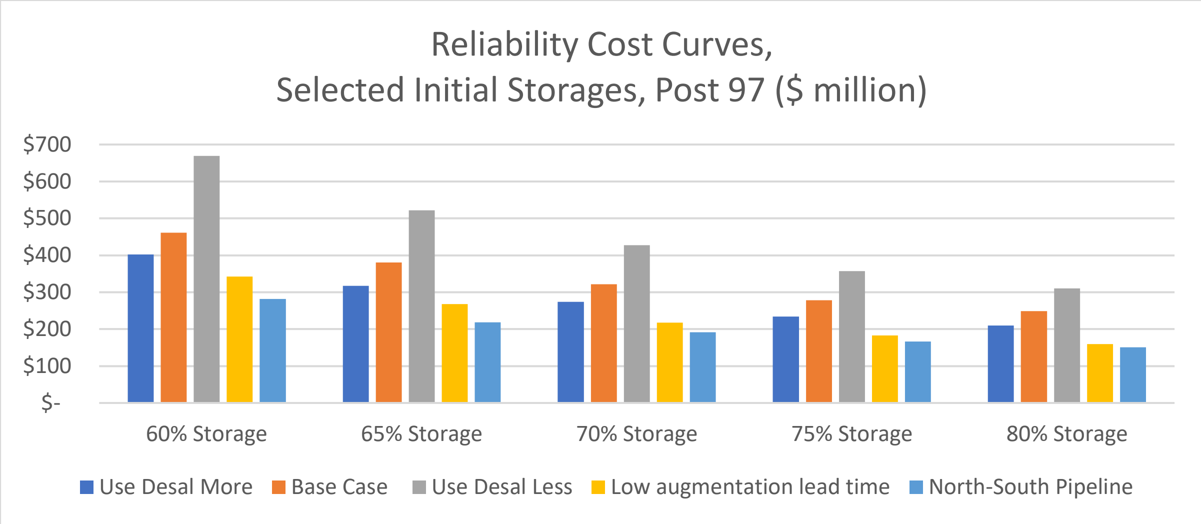

Figure 5: Reliability costs for alternative scenarios and selected initial storages, Post 97 inflows.

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Introduction: The economic value of water in storage

This report establishes the economic value of water in storage in Melbourne's supply system. It does so by examining the costs associated with maintaining a reliable water supply over a twenty-year timeframe. Calculating this cost over a range of initial storages generates the Reliability Cost Curve (RCC) for Melbourne, which in turn, shows how the value of water in storage changes at different levels of storage. Knowing the value of water in storage is critical for a range of important issues confronting the Melbourne's water supply authorities. These include:

- water trading, particularly at what price to buy or sell water;
- quantifying the water security benefits of Integrated Water Management and local scale investments in efficiency;
- informing the operation of the desalination plant, or other climate independent water supply sources; and
- determining the real option value of forward planning.

The existence of water supply sources that cost more to operate than gravity fed reservoirs, such as desalination plants, requires a procurement policy that incorporates the contribution these water sources make to the reliability of the entire system. Examining how the cost of maintaining a reliable water supply changes as the storage level changes provides important information as to when climate independent water supply sources should be accessed. In addition, it can also inform a variety of other water utility decisions, such as trading water. Given the South Central Market Trial, which allows trading of water, the RCC provides critical additional information to help delay or avoid costly additions to the water grid. It helps identify trade opportunities while also addressing the need for water security during long periods of drought.

As the RCC is calculated for a range of initial storages and future storage volumes, it includes decision making arrangements for expanding the water supply system arising from a series of occasions when Melbourne's water supply system is augmented for the purposes of this study by the construction of additional desalination capacity. As such, the design, approval and construction time influences at what storage level the augmentation is triggered to guarantee a reliable water supply. By reducing the time it takes to build an augmentation into discreet steps, the value of each step can be determined by comparing the RCC with alternative augmentation triggers. This method provides a means of calculating the real option value associated with reducing the timing of augmentations to the water supply system by implementing the early steps for an augmentation while storage levels are high, thereby enabling the decision to commence construction to be delayed until it is essential and then be implemented quickly.

It is possible to quantify the cost of maintaining a reliable water supply for Melbourne because of the construction and operation costs of climate independent water supply sources, such as the VDP at Wonthaggi. In practice, these climate independent water supply sources now represent the upper bound on the costs of maintaining supply for major cities and this enables more robust estimates of cost than measures to identify the social losses incurred with a failure to supply essential for life water. Having a concrete estimate of costs associated with water shortages allows for a more complex examination of the way in which the water supply system is operated.

This report sets out how the RCC for Melbourne's water supply system was calculated and then a series of scenarios that examine how it changes under different conditions are explored. The RCC will be calculated using existing operating arrangements, including existing reliability standards to determine an augmentation trigger for an expansion of the water supply system, to establish the probability and time discounted cost of maintaining reliability at all levels of storage. This requires creating a model of Melbourne's water supply system that can closely approximate the results of the complex REALM model used by Melbourne Water. The model needs to be designed to enable fast Monte Carlo simulation for system behaviour analysis to determine the reliability of the water supply system over time.

The conceptual model created of the Melbourne water supply system simulates the system head works, plus Cardinia Reservoir, to meet demand allocated to three zones: Cardinia, Sugarloaf, and "the rest" (Figure 6). The model operates on a monthly time step and accounts for a range of assumptions about various scenarios. The model includes:

- Stream inflows;
- The head works storages;
- Releases to downstream for environmental purposes;
- Evaporative losses from Cardinia, Sugarloaf, Tarago and Yan Yean reservoirs;
- Capacity constraints at various points around the system, particularly in bulk water transfers and pumping;
- Operation of the VDP and potentially of the North-South pipeline as a scenario;
- Possible augmentation of the VDP and construction and augmentation of a second desalination plant;
- Melbourne metropolitan and regional water authority demands. The Melbourne metropolitan demand is represented as the combination of a base component and a variable component following the approach in the REALM model. The variable component is weather dependent and subject to restriction.

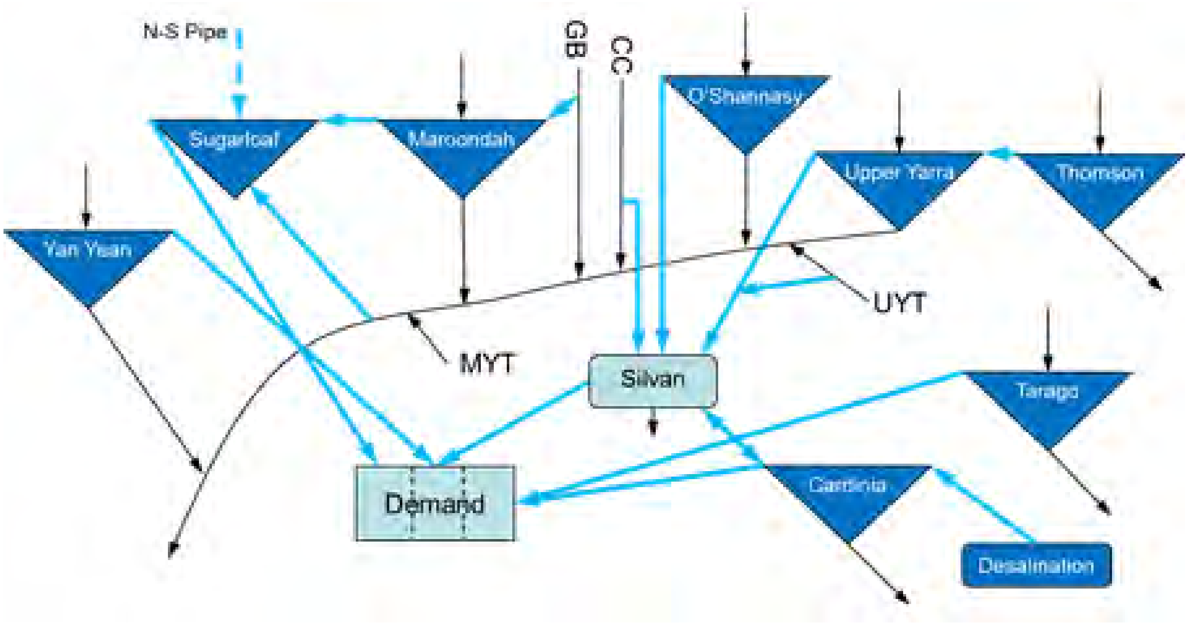


Figure 6: Melbourne's water supply system as represented in the conceptual simulation model.

The details of this model, and its validation in comparison with the REALM model, are described in Chapter 3.

The basis for calculating costs associated with maintaining a reliable supply of water are described in Chapter 2. These costs are described for existing operating arrangements in the base case. In addition, there are a range of scenarios examined in the report. Each scenario has alternative operating arrangements and costs associated with it and calculates the associated expected costs associated with supplying water over the planning period. They are also outlined in Chapter 2.

Chapter 1: Costing water reliability

Australia has a notoriously uncertain climate. In order to provide reliable supplies, city water authorities have typically harvested stream flows and built large storage reservoirs to accumulate large water holdings. Historically, water security has been maintained in times of water shortage by imposing restrictions on current demand, and implementing demand management strategies, so that there would be sufficient water in storage to meet future demand. In this context, reliability is maintained either through more dams or more restrictions and is difficult to explicitly quantify the cost. However, the advent of climate independent water supply sources, such as desalination plants, mean that it is possible to quantify the costs associated with reliability as potential water shortages can be met through expansions of the water supply system which have fixed and defined costs.

The challenge associated with basing water security entirely on restrictions is that it left the Melbourne water supply system very vulnerable to extreme conditions. Rob Skinner, CEO of Melbourne Water during the Millennial Drought, described the systems resilience as follows:

> "The streamflows into Melbourne's major reservoirs illustrate that over the 90 years of recorded data, up until 1996, there had been regular cycles of variation in annual inflows…these variations had a frequency of approximately 20 years.
>
> So in 2005, in the absence of any strong scientific evidence to the contrary, it would have been reasonable to assume that the Melbourne catchments were in the trough of a regular long-term cycle… By the time the reservoirs were less than 30 per cent full, in 2007, with significant uncertainty around whether the storages would refill to any secure level in the foreseeable future, the resilience of the system was very low." *Page 131, (CEDA, 2011)*

Relying on restrictions and demand management has meant it was difficult to quantify the cost of maintaining reliability in a water supply system in the past. However, having the ability to deploy reliable climate independent water supply sources provides an alternative means of quantifying short-term risks to the water supply system. Rather than risk experiencing 'catastrophic' water shortages, an unnecessary or pre-emptive augmentation may be undertaken.

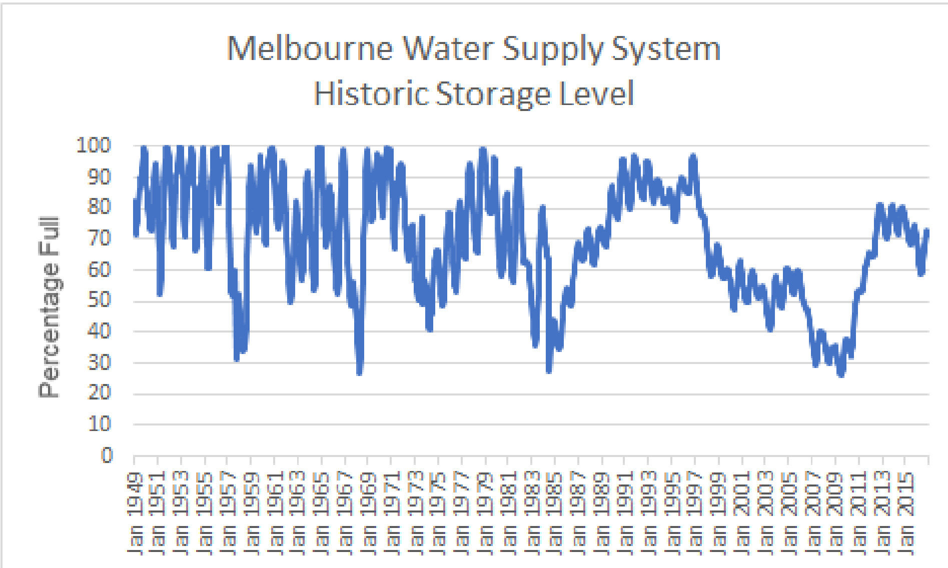


Figure 7: Melbourne's water supply system storage, 1948 to 2016

As the historic water storage levels suggest, high initial water storages at the beginning of the Millennium Drought (2001-2009) ensured Melbourne's water security at the start of the drought. These high-water storages meant that the Melbourne water supply system, which provides approximately 400,000 megalitres to households and businesses annually, was deemed to have robust reliability in 2005 and 2006 (Howe, 2005 #40), even after nearly a decade of drought. Yet, following a year of record low inflows, in 2007 it was determined that water storages were at a critical level. The system was expanded to include a desalination plant capable of producing 150 gigalitres per year. This experience reflects the role that climate independent water supply sources play in underpinning a reliable water supply and how they interact with storage levels.

The response of augmenting water supply systems with climate independent water supply sources is not unique to Victoria or Australia. A similar response to emerging water shortages was adopted by water authorities around Australia and around the world when facing supply uncertainty. Consider the case of the City of Santa Barbra which constructed a desalination plant in 1991. It was only used between March and June in 1992, and then shut down as the drought broke. It was not until November 2016 that it was recommissioned in the face of another period of short supplies (Hamilton, July 22 2015).

This report aims to quantify the costs of maintaining reliability over a long-term planning period so that it is possible to inform actions to minimise future hydrological risk and economic costs. The study does this by assuming the water supply system can be expanded with a hypothetical climate independent water supply sources, such as desalination plants, to avoid water shortages. While it is not possible to completely eliminate hydrological risk, particularly extreme events such as the inflows that occurred during 2006, it is possible to be prepared for them. This is particularly important given that the state water grid has been expanded significantly.

Water security now requires assessing the costs and benefits of using water in storage against a variety of other actions. For example, other actions might include, buying water on the market (subject to market rules), using desalinated water, harvesting stormwater, implementing further demand management actions or imposing restrictions. This requires a clear assessment of the costs of supplying water from alternative sources and the benefits of having water in storage in the future. Some costs are clear, with the price of accessing water from the desalination plant as an example. Others are more difficult to determine, such as the social costs incurred when water restrictions are imposed.

Most of Victoria's water systems are now more reliable and can benefit from clearly articulating the trade-offs between risk and the cost of supply as the population they service continues to grow and the climatic conditions remain uncertain. An economically based assessment method that rigorously incorporates the impact of hydrologic uncertainty can be used to inform operational planning and decisions as Melbourne's diverse water supply system has explicit costs to access water from high reliability sources but no corresponding measure of the benefits. This report sets out a methodology for calculating the expected cost of maintaining a reliable water supply and how this cost changes as storage levels change. Thereby defining the value of water in storage.

Water value function

The concepts underpinning the proposed RCC, and the corresponding value of water in storage, have a long history in hydroelectricity power generation. For a reservoir operator managing a hydro power plant, the objective is to maximise the profit from releasing water during the period and from saving water for generation in future periods. The marginal value of water in storage for a hydroelectricity power generator is "the price at which water will be traded between the two" (Scott, 1998 #110).

The typical shape of the marginal value of water in storage for a hydro power generation reservoir is that when storages are low, the marginal value of water is high. Conversely, when storages are high, the marginal value of water is low. The marginal value of water curve is relatively flat for most levels of storage, falling to zero at the upper bound, but rising much more steeply as storage decreases towards its lower bound (Tipping, 2007). This reflects the fact that the system is able to cope with a wide variation of inflows, and hence storage levels, at moderate cost, unless storage reaches fairly extreme levels, in which case water becomes very valuable as a means of averting a significant probability of shortage.

Hydropower generation has very different risk factors to the water supply sector, particularly with regards to the essential for life service delivery. While energy is critical to provide, there are a wider range of options available to produce it, from alternative power stations or even diesel generators, so that the risk of failure is less dependent on water availability. In contrast, for water supply, forward planning to ensure that water is available for essential for life water services with growing population and changing preferences is critical. The difference between the marginal value of water in storage used for generating hydroelectirc power versus underpinning an urban water supply system is the socialised 'risk of failure' in the latter case. In essence this socialised risk relates to governments stepping in to invest to avert a crisis.

The value of water in storage for an urban setting relates to how it contributes to avoiding the costs associated with avoiding water shortages. Given the ability to construct incremental volumes of capacity by building climate independent water supply sources, the costs of failure are avoidable through the contribution of additional climate independent water supply sources.

For the purpose of this study, 'failure' is defined as when storages reach low or minimum volumes when shortages would occur between supply and restricted demand. This provides a basis for assessing the various scenarios considered in this report.

Value of water in storage for an urban water supply system

Similar to the hydro power generation challenge, the value of water in storage has been approximated by a comparison between consuming it today versus storing it and consuming it in a future period. Typical analysis of the reservoir operation decision is described in Figure 8. This outlines the choice for a reservoir operator to either to release all water available, described as the Standard Operating Policy (SOP) articulated by Maass et al. 1962 and Loucks et al. 1981, or to restrict the amount of water released and hold some water in storage to hedge against future, more substantive, losses.

In essence, the SOP places the highest priority on releasing water for immediate beneficial use, up to the level of target demand, after which remaining water available is stored until storage capacity is reached. Having a fixed target demand is typical of the approach adopted by hydrologists (Harou, 2009). The hedging line, reflecting the imposition of a restrictions regime, represents putting aside water in current consumption, even when it may be available so that it may be used in the next period.

In Figure 8, the SOP release rules are:

$$D_t = S_{t-1} + In_t \qquad \text{if } S_{t-1} + In_t \leq D_{target} \qquad \text{1a}$$

$$D_t = D_{target} \qquad \text{if } D_{target} \leq S_{t-1} + In_t \leq S_{cap} \qquad \text{1b}$$

$$D_t + Spill_t = D_{target} \qquad \text{if } S_{t-1} + In_t - D_{target} > S_{cap} \qquad \text{1c}$$

The exact cost of reliability settings established by hedging the SOP are hard to quantify. However, having the capacity to augment the water supply system within the timeframe of system memory means that there is the capacity to avoid the catastrophic failures that past hedging, or restrictions, regimes and it has explicit costs associated with it. With climate independent water supply sources available, it is theoretically possible, although expensive, to meet the target delivery even when there is no water in storage through the construction of additional theoretical desalination plants. To decide when to operate the desalination plant, and when to augment the desalination plant capacity further, requires understanding the cost of maintaining the desired level of reliability.

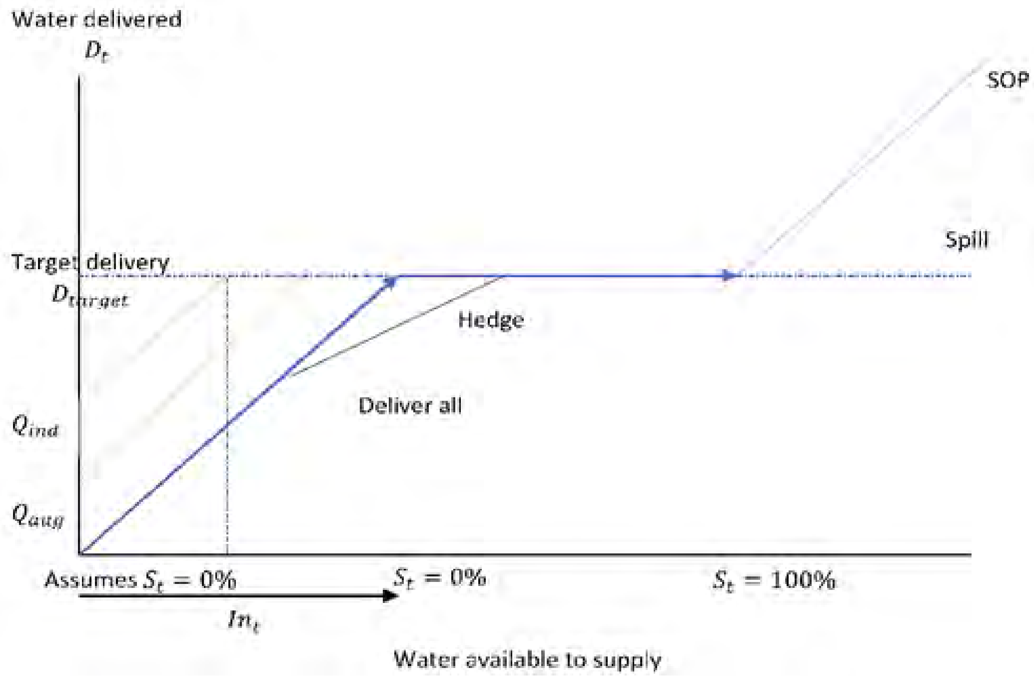


Figure 8: The Standard Operating Policy, hedging, existing desalination plant and augmentation. D_t is the quantity delivered in period t, In_t is the inflows to the system in period t, D_{target} is the amount demanded by consumers given the fixed costs associated with the water supply system, S_t is the storage at time t.

With the advent of engineering solutions that can be deployed in the face of potential water storages, the cost of maintaining a level of reliability can now be quantified. By considering the time and probability discounted costs associated with existing operating arrangements, set in the context of expected inflows and projected demand growth, an estimate of the cost functions for maintaining a reliable water supply across a range of initial storages can be made. Evaluating this cost estimate over the range of initial storages, from completely full to almost empty, illustrates how the expected costs of maintaining a reliable water supply change. This is the Reliability Cost Curve. Examining how the RCC changes as the level of water in storage changes provides an estimate of the economic value of water in storage.

To develop an expected cost associated with delivering a reliability water supply requires a hydrological model of the water supply system, and an understanding of the current operating arrangements, costs and augmentation triggers.

Chapter 2: Costs associated with maintaining a reliable supply of water

Estimating the costs incurred in maintaining a reliable water supply for Melbourne requires the operating arrangements, and the direct associated costs of additional increments of water supply, to be described. These costs do not include those incurred in operating the water supply system, nor the benefits associated with running hydropower generation, but are the incremental costs associated with maintaining a reliable water supply. This is because the study is examining the value of water in storage, and this value is derived from its capacity to avoid or delay additional augmentations to the system. As such, the study is not considering the costs associated with existing infrastructure that do not vary with water supply availability. Since the water supply system will be examined at a range of initial storages, from full to nearly empty, quantifying the cost of reliability requires a range of measures to secure supplies to be costed, such as additional augmentations to the water supply system. In addition, a range of scenarios, each of which alter the costs of maintaining reliability, will also be examined. The relevant costs are:

1. The operating costs associated with operating the desalination plant (pre and post augmentation);
2. The pumping costs from Cardinia to Silvan for water from the VDP, with and without augmentation;
3. The social costs associated with the restrictions regime;
4. The capital costs associated with augmenting the Victorian Desalination Plant;
5. The costs of additional hypothetical augmentation scenarios (post a 50GL expansion of the VDP);
6. The costs associated with operating the North-South Pipeline, including both the pumping and treatment costs and the opportunity cost of using the water under the current permitted operating arrangements; and
7. The social costs associated with any supply deficits that occur when the water supply system cannot meet Stage 4 restricted demand.

It is also important to outline how the time value of money associated with the capital costs of any augmentation. These costs and approach to quantifying the time value of money are explained below. Since the costs are presented in present value terms they require an appropriate interest rate to calculate to complete the calculation. These costs are summarised in Table 6 for the Base Case. In addition, the operating arrangements will be changed to examine how they change the overall cost of maintaining a reliable level of water in storage under different operating scenarios.

Operating costs of the desalination plant

Construction of the VDP was announced in 2007 during the Millennium Drought, when storage levels were critically low. The plant can deliver up to 150 billion litres of high-quality drinking water a year. For the purpose of modelling in this study, the decision to operate the Victorian Desalination Plant, located at Wonthaggi, is based on January storage levels. If the storage levels are below a defined action point, or trigger storage level, then it is assumed that an order is placed for the VDP to produce a certain quantity within the coming year.

Table 1 describes the assumed quantity of water ordered, and what defined storage levels, of the existing desalination plant and the amount that would be ordered with the additional expansion in place. These are the base case operating arrangements for the desalination plant and were identified by the Steering Committee as reflecting the existing ordering principles based on Melbourne Water's adaptive water management principles.

Table 1: Victorian Desalination Plant operating arrangements and costs

S_t (at end April)	ML order (Pre-augmentation)	ML order (Post augmentation)	Operating cost (/ML)
$S_t \geq 0.65$	0	0	$0
$S_t < 0.65$	50,000	66,700	$560
$S_t < 0.625$	100,000	133,300	$590
$S_t < 0.6$	150,000	200,000	$610

Silvan pumping costs

When the VDP is operated at higher levels of production it can incur pumping costs associated with moving water from the Cardinia to Silvan Reservoirs. This pumping is required to ensure that the manufactured water can be allocated to water demand. Silvan pumping costs are $41.41/ML when the pumping is operated. The system model estimates the pumping volumes.

Economic and social costs of Restrictions

A component of Melbourne's water security adaptive management framework is the existing restrictions regime. This regime imposes costs because it limits the use of water in an attempt to reduce water consumption during periods of shortage. While some of these costs, such as those incurred by the water utilities in managing the water restriction regime, are explicit, others are borne by water consumers and are indirect and unquantified. The social costs of restrictions include the tangible costs incurred by water utilities, as well as the lost amenity to consumers, that is, the total economic cost associated with the restrictions regime. Appendix 1 discusses how the social costs of restrictions have been quantified in academic studies and applied to this report.

The water restrictions applied by Victoria's urban water authorities include limitations such as:

- Stage 1 restrictions:
  - Gardens and lawns can be watered by hand at any time
  - A watering system can be used on alternate days during restricted hours
  - Cars can be washed at any time
  - New pools can be filled. Existing pools can be topped up at any time.
- Stage 2 restrictions:
  - No watering of lawns
  - Gardens can be watered by hand at any time
  - A watering system can be used on alternate days during restricted hours
  - Cars can be washed at any time
  - New pools can be filled. Existing pools and spas can be topped up on alternative days during restricted hours.
- Stage 3 restrictions:
  - No watering of lawns
  - Gardens can be watered by hand or using a watering system on alternate days during restricted hours
  - Car washing restricted to windows, mirrors, lights and registration plates
  - New pools cannot be filled. Existing pools and spas can be topped up on alternative days during restricted hours.
- Stage 4 restrictions:

- No watering of lawns or gardens at any times. This includes residential, commercial and public areas.
- Car washing restricted to windows, mirrors, lights and registration plates
- New pools cannot be filled. Existing pools can be topped up by bucket.

The estimated volumetric savings from these restrictions, based on modelling of zones for the adaptive management framework were:

Table 2: Estimated water savings from restrictions

Stage of restriction	Estimated range of savings (of total demand)	Assumed savings
1	2-3%	2.5%
2	5-7%	6%
3	8-12%	10%
4	14-16%	15%

Water for Victoria proposed that water corporations, local government, catchment management authorities and community leaders work together to enhance public open space through integrated water management in our existing and new urban environments. This will be achieved through a better understanding of the benefits associated with water use. It will also be informed by understanding the costs that water restrictions impose on the community, and using this to inform water supply and demand management decisions (Victorian Government, 2016).

To estimate the social costs associated with restrictions in line with the proposal in *Water for Victoria*, DELWP instigated a cost of restrictions project. Marsden Jacobs and Associates undertook analysis that applied estimates of the social costs associated with restrictions to the Victorian restrictions regime and prepared costs that could be used in water resource models. Household costs incurred due to restrictions are based on McNair and Ward (2012). Business Costs are based on Henscher (2006). Public Open Space costs are based on Weller & English (2008). Water Corporation Costs are based on Marsden Jacobs and Associates analysis of publicly available financial data.

Table 3 gives the costs used in the analysis for this study. The social costs of restrictions include the costs to households, businesses, public open space and water corporations. The costs are initially high due to the expenses incurred by water utilities in communicating the restriction requirements to customers. These communication costs are incurred consistently at the same amount. As more water is restricted, the communication costs are spread over a larger amount of saved water. However, the costs to consumers of restrictions increase.

Table 3: Assumed restriction regime operating arrangements and social costs

Stage of restriction	Trigger storage level	Social costs per Ml
1	$S_t < 0.65$	$3,310
2	$S_t < 0.50$	$3,090
3	$S_t < 0.40$	$2,700
4	$S_t < 0.30$	$7,390

Operating the North-South Pipeline

The North–South Pipeline, also known as the Sugarloaf Pipeline, is a 70 kilometre pipe that can carry water from the Goulburn River to Melbourne Water's storage at Sugarloaf Reservoir. It was constructed as part of a suite of major water augmentation projects announced by the then Victorian Government in 2007 during the midst of the Millennium Drought. The pipeline was an option to deliver a substantial volume of water to Melbourne in a relatively short timeframe. The pipeline was scheduled to be completed 18 months ahead of the VDP. Furthermore, the shortfall between inflows and demand in 2007 was approximately 250 GL, which was 100 GL more than the capacity of the VDP. The North-South Pipeline can transfer up to 75 GL annually to Melbourne's water supply.

Melbourne's urban water retailers will hold entitlements and hence allocation in three water trading zones when the Connections project in Victoria's northern irrigation districts has been completed and savings verified. These zones are the Greater Goulburn 1A, Murray Zone 6 (Dartmouth to Barmah) and Murray Zone 7 (Barmah to SA Border). While there are practical restrictions on the amount of water that can be accessed from these three zones, due to the physical limits on how much water can be moved through the Barmah Choke reach of the River Murray, this will not be incorporated within the modelling of the North-South Pipeline. Instead, the modelling of the North-South Pipeline has created an estimate of the price and associated availability of Melbourne's urban water retailer's entitlements. Some infrastructure upgrades within the Melbourne regional distribution system would be required to fully utilise the North-South pipeline. These have not been included in the scenario modelling undertaken in this study.

Operating rule

The North-South Pipeline operating arrangements are made as obligations in the Statement of Obligations (System Management). In broad terms the operating arrangements restrict the use of the North-South Pipeline unless Melbourne's total system storage levels are less than 30 percent. In the Base Case being examined, the trigger point for the North-South Pipeline will be the storage levels in January. This operating rule will be varied in the scenarios being examined. Further details of this scenario are set out in Table 7.

Costs of accessing North-South water

Operating costs for the North-South Pipeline include the market price of water, the opportunity cost, plus pumping and treatment costs. The pumping costs associated with operating the North-South Pipeline were assumed, based on Melbourne Water Corporation estimates, to be $199 per ML. Incorporating the opportunity cost of using the North-South Pipeline transfers requires estimating the price to trade entitlements. As the price to trade is influenced by water availability and the price at which it is trade, it requires an estimate of Goulburn Storage and, given the stochastic modelling of water availability, should also include an estimate of the link with the hydrological conditions in the Melbourne system.

This study estimates the opportunity costs associated with accessing Melbourne's entitlements. These costs depend on the volume of water available in the Goulburn, which influences the temporary water trade price. A model to obtain the price was developed in two steps:

1. The volume stored in the Goulburn is predicted from a relationship with major Melbourne system inflows, developed using observed Melbourne inflows and storage levels simulated by the Goulburn System Model described below.
2. The price is the related to the volume.

Goulburn Storage

The storage in the Goulburn system in December was estimated using a reference Melbourne system inflow. The storage in the Goulburn system (Eildon and Waranga Reservoirs) was obtained from the Department of Environment, Water, Land and Planning Goulburn System SDL model (Run C919), which is the best available representation of current conditions (K. Jusuf, Pers. Comm. 4 Oct 2017).

Storage was estimated using a logistic regression between storage level, the current calendar year inflow and the previous calendar year inflow, using:

$$log\left(\frac{S}{1-S}\right) = \beta_0 + \beta_1 Q_0^{0.5} + \beta_2 Q_{-1}^{0.5} \qquad 2$$

where *s* is the fractional storage (converted to volume using a capacity of 3763GL (the maximum value in Run C919)), and *Q* is the sum of the calendar year flows into Maroondah, O'Shannassy, Upper Yarra and Thomson reservoirs. The residual in predicted storage volume, ε_r, was calculated. The model was fitted using data from 1913-2013 and the regress function in the computer program MatLab. Residual analysis showed ε_r to be serially correlated, with a lag-1 correlation of 0.40. To obtain storage values within the RCC analysis, the regression equation was used and serially correlated errors were added to create a set of stochastic realisations of storage. The stochastic residual model was

$$\varepsilon_{r,i} = \varepsilon_{w,i} + \rho\, \varepsilon_{w,i-1} \qquad 3$$

where ρ is the serial correlation and ε_w are independent and normally distributed. Table 4 shows the model coefficient values and statistics. Figure 9 shows the data and an illustrative simulation.

Table 4: Goulburn storage model coefficients

β_0	β_0	β_0	ρ	$\overline{\varepsilon_w}$	$\sigma_{\varepsilon w}$ (GL)
-5.45	0.0077	0.0018	0.40	0	369

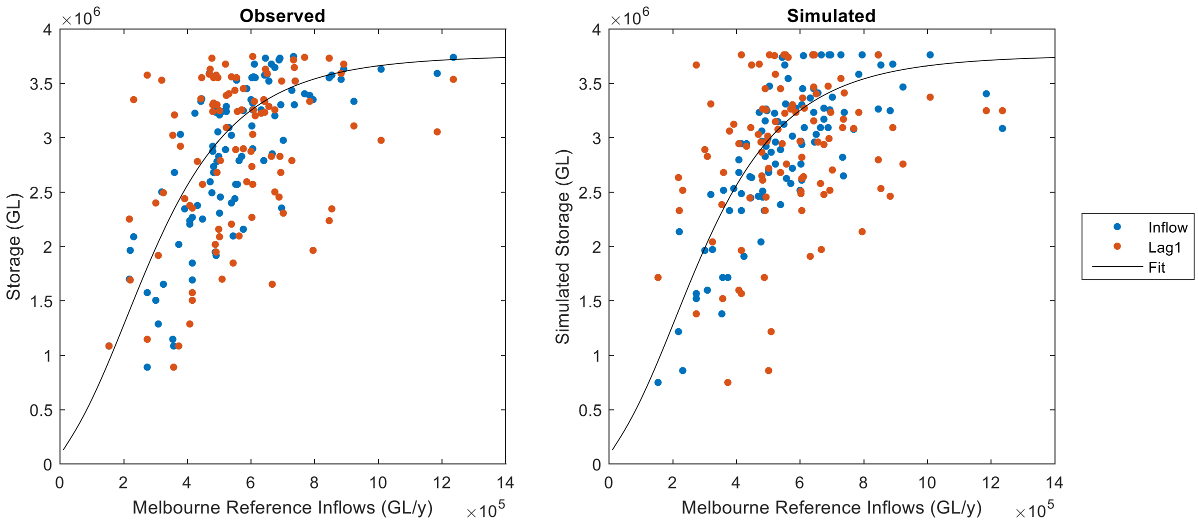


Figure 9: The fitting data (left) and a simulation from the Goulburn Storage model (right).

Goulburn trade price

The trade price for water in the Goulburn is a reasonable estimate of the opportunity cost of using water in Melbourne compared with use in the Goulburn. That is to say, the opportunity cost of using water entitlements is the price at which they could be sold. This price was estimated using a regression between the Goulburn Storage and monthly trade price between July 2009 and April 2017. The prices are most stable and representative of major trade in the main part of the irrigation season (Figure 10). Regressions based on October to February and based on December data only were considered. As the resulting models were very similar, the December model was used. The trade price of water was estimated as:

Price = 450 – 0.122 * Storage Volume 4

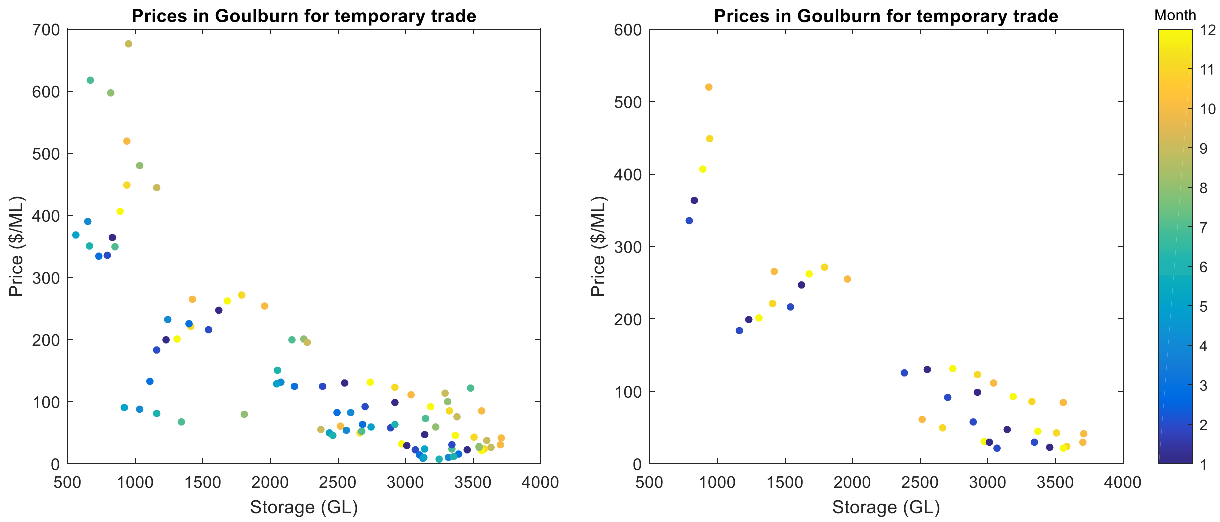


Figure 10: Price as a function of storage (Eildon plus Waranga Reservoirs) in the Goulburn System. Left shows all months and right shows October to February.

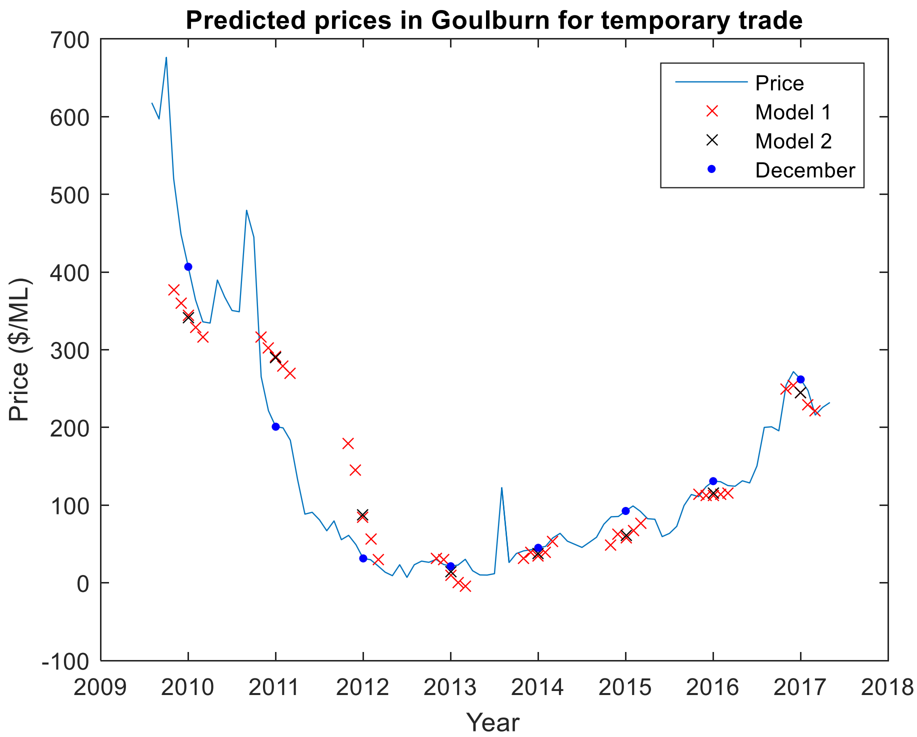


Figure 11: Comparison of observed and estimated water trace prices in the Goulburn System. Model 1 used October to February data. Model 2 used December data.

Capital costs associated with augmenting the Victorian Desalination Plant

The VDP has the capacity to be augmented by an additional 50,000 /y. This would raise its annual capacity to produce water to 200,000 ML/y. For the purpose of this study, this expansion is assumed to require a capital expenditure of $720 million.

The base case assumes that this expansion will have the following timings:

1. Investigation/design/approvals: approx. 1 to 2 years
2. Construction: around 2 years
3. Commissioning: 3 to 6 months

In the Base Case it is assumed that the entire construction and commissioning process takes 3.5 years.

Augmentation Trigger

The need for augmentation of the VDP depends on future stream flows and demand growth. Based on current streamflow and population forecast scenarios it is not expected until approximately 2035 (Water for Victoria, Figure 5.2, page 87). However, the modelling in this report is based on thousands of potential streamflow scenarios and across a range of initial storages. In some of these scenarios the VDP is augmented sooner than 2035. The modelling used in this study implements a decision rule for augmenting the VDP (and subsequent augmentations) based on storage levels in January. These arrangements were developed based on current planning guidelines and advice of the steering committee. The expansion of the VDP will only occur when storages are at critically low levels. As a consequence, the level of storage at which the augmentation is triggered, S_{aug}, is calculated as:

$$\boldsymbol{S_{aug} = t_{lead}\left(\bar{D} - Q_{desalCap} - Q_{driest}\right) + \beta S_{cap}} \qquad 5$$

where t_{lead} is the lead time for construction and commissioning, Q_{driest} is the lowest observed annual harvested inflow over the relevant period, $Q_{desalCap}$ is the desalination plant capacity, β is the critical proportion of storage and S_{cap} is the system active storage capacity. $\bar{D}$ is the demand for the relevant years averaged over different weather scenarios; that is the demand for an average rainfall year. $\boldsymbol{Q_{driest}}$ is varied with lead time. This trigger was adjusted as described earlier to account for population growth and augmentations.

Values for $\boldsymbol{Q_{driest}}$.were selected based on net harvested inflows for the period 1996-2016 for periods of time corresponding to the assumed lead time. The annual net harvested inflow was estimated as the annual consumption plus the increase in storage across the year. The lowest 1, 2, 3, and 4 year sequences were found and the standard deviation of these sequences was also found. Two estimates of minimal inflows were compared – the lowest observed value and the mean minus 2 standard deviations (Table 5). A compromise value was selected for use reflecting a compromise between the two inflow estimates and the criteria that the augmentation trigger should increase with lead time. In the simulations, $\boldsymbol{Q_{driest}}$=180GL/y was used for 2 year lead times and $\boldsymbol{Q_{driest}}$=200GL/y was used for 3.5 year lead times and 210GL/y was used for 5 year lead times. The value used for subsequent augmentations, reflected the expected lead time for that augmentation. As an additional check for too low conditions, if the storage volumes fall below 500,000 ML in any month, then the augmentation with associated timing will also be triggered.

Table 5: Low inflow occurrence

Continuous period	1 year	2 years	3 years	4 years
Lowest observed (GL)	103	244	264	299
Mean less 2 standard deviations (GL)	116	188	222	260
Value used (GL)	120	180	210	240

Additional augmentations

Under certain hydrological assumptions, when water storages are low, the reliability of Melbourne's water supply system requires additional augmentations. Water for Victoria (Figure 5.2, page 87) suggests that this shortfall will be made up by recycled water, stormwater and other yet to be determined sources. It is assumed, for the purpose of this study, that any additional water requirements are met through additional desalination plants.

For the study, the additional desalination plants will have the same augmentation trigger arrangements as the existing Victorian Desalination Plant. The reason that the capital costs are lower for the additional expansion is that the peripheral infrastructure (the pipelines, inlet and brine disposal structures etc) needed for the desalination are typically sized for to allow for expansion of the desalination plant allowing the expansion to be made at a relatively lower unit capacity cost. The capital costs are assumed to be:

- A capital cost of $1,950M for an initial 50 GL/y plant (and a 100 GL final capacity).
- Additional expansions are assumed to be built in conjunction with this hypothetical plant. As a consequence, an expansion of this additional desalination plant by 50 GL per annum is assumed to $720 million.

The lead times for the additional augmentations is assumed to be:

- Five years for the additional desalination plant to be planned and constructed; and
- Three years for the expansion of the additional desalination plant to be constructed.

The expansion of the additional desalination plant has a shorter timeframe because it would utilise existing desalination plant infrastructure, thereby requiring less construction and approvals work.

In total, this study incorporates three hypothetical desalination plant augmentations. The first is the expansion of the VDP. The second is the construction of a new desalination plant, and the third is an expansion of this new desalination plant. These hypothetical expansions are included in this study to address low storage volumes.

Capital costs associated with pre-emptive augmentation

The capital costs associated with the augmentation will be determined by the formula:

$$\boldsymbol{K}^{*}(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}} \qquad 6$$

Where K^* is the real capital cost, *t* is the time at which it is built (relative to the start of the simulation), and *r* is Melbourne Water's weight adjusted capital cost. This provides the present value cost of additional augmentations to Melbourne's water supply system.

Social costs associated with water supply system failure

In a small number of the modelled hydrological realisations, Melbourne's water supply system fails to have sufficient supply to meet Stage 4 restricted demand. For the purpose of this study, this is deemed to be a 'failure' of the water supply system. Modelling shows the water supply system failures occur for simulations with very low initial storages (<40%). It is assumed that there are very high social costs associated with not meeting Stage 4 restrictions.

The social costs associated with not meeting Stage 4 restricted demand are assumed to be similar to those used in stochastic modelling by (Grafton, 2014) when estimating a scarcity price for Sydney's water supply system. The social costs of water shortages were estimated based on the experience of the Barcelona utilities who imported bulk water by sea in 2008 when confronted with low reservoirs. These costs are $30,000 per ML.

Appropriate interest rate

The appropriate interest rate to discount the costs of maintaining a reliable water supply is based on Melbourne Water's post tax real interest rate of 4.2 per cent.

Base case

The Base Case being examined is summarised in the table below:

Table 6: Base operating arrangements and costs being examined

Storage level	Reliability Measure	Cost ($/ML)
$S_t < 0.65$	Desalination order placed (1/3 of installed desalination capacity or 50,000ML pre-augmentation and 66,700 ML post augmentation 1)	$560
$S_t < 0.625$	Desalination order placed (2/3 of installed desalination capacity or 100,000ML pre-augmentation and 133,300 ML post augmentation 1)	$590
$S_t < 0.6$	Desalination order placed (full desalination capacity or 150,000ML pre-augmentation and 200,000 ML post augmentation 1)	$610
	Pumping costs associated with desalinated water	$41.41
$S_t \leq 0.60$	Stage 1 Restrictions (reducing demand by 2.5 per cent)	$3,310
$S_t \leq 0.50$	Stage 2 Restrictions (reducing demand by 6 per cent)	$3,090
$S_t \leq 0.40$	Stage 3 Restrictions (reducing demand by 10 per cent)	$2,700
$S_t \leq 0.30$	Stage 4 Restrictions (reducing demand by 15 per cent)	$7,390
$S_t \leq 0.30$	North-South Pipeline opportunity cost	The cost will vary, based on modelling
	North-South Pipeline pumping costs	$199
$S_{aug} = t_{lead}(\overline{D} - Q_{desalCap} - Q_{driest}) + \beta S_{cap}$	Augmentation of the Victorian Desalination Plant (βS_{cap} adjusted for population growth) $t_{lead} = 3.5$y $\beta = 0.4$ Q_{driest}=180GL/y	$600 million for a 50 GL/y expansion
$S_{aug} = t_{lead}(\overline{D} - Q_{desalCap} - Q_{driest}) + \beta S_{cap}$	Construction of new desalination plant $Q_{desalCap}$ adjusted to reflect increased capacity	$1,623 million for an initial 50 GL / annum capacity plant
$S_{aug} = t_{lead}(\overline{D} - Q_{desalCap} - Q_{driest}) + \beta S_{cap}$	Augmentation of new desalination plant $Q_{desalCap}$ adjusted to reflect increased capacity	$600 million for a 50 GL/annum expansion
	Additional capital expansion $\boldsymbol{K}^*(\mathbf{1}+\boldsymbol{r})^{-\boldsymbol{t}}$	
Failure to supply stage 4 restricted demand	Social costs associated with not meeting Stage 4 restricted demand	$30,000 /ML

The trigger storage levels will change over the planning period as the population grows, as described later (page 20). The trigger volumes used for desalination water are used for modelling purposes in this study and are not used by the water businesses in determining the current desalination water order advice.

Scenarios

The cost of reliability will be examined under a range of scenarios. These scenarios alter key components underpinning the reliability of Melbourne's water supply system. These scenarios are used to examine the economic value of water in storage resulting from variations on the Victorian Desalination Plant's operating arrangements, the North-South Pipeline operating arrangements, and the timing and volumes at which augmentations might occur.

The consequence of altering the desalination ordering arrangements will be examined by changing the assumed storage trigger levels. While the amounts and costs of desalinated water will remain the same, the trigger storages will be altered. This will be examined through a 'high' trigger storage and a 'low' trigger storage.

Scenario 3 will examine how the costs of maintaining reliability change from the Base Case should the operation of the North-South Pipeline be able to be triggered at a higher level of storage. This scenario will examine how the cost of maintaining the reliability of the Melbourne water supply system changes as the arrangement of the augmentation decision changes. The scenario does not consider the implications of additional volumes diverted from the Goulburn system and was undertaken to broadly assess the sensitivity of the economic value of water in storage to variations in operating policies and principles. In particular, what the consequence of reducing the time it takes to augment the water supply system is for the cost of maintaining the reliability of the system.

In Scenario 4, the lead time of the augmentation of the VDP is reduced from 3.5 years to 2 years.

Table 7: The four alternative scenarios operating rule changes

	Operational change	New operating rule
Scenario 1 Use Desal Less	Desalination ordering New trigger levels	$S_t < 0.55$ $S_t < 0.525$ $S_t < 0.50$
Scenario 2 Use Desal More	Desalination ordering New trigger levels	$S_t < 0.75$ $S_t < 0.625$ $S_t < 0.60$
Scenario 3 Use NS Pipeline More	North-South Pipeline New trigger levels	$S_t < 0.70$
Scenario 4 Reduced augmentation time	Augmentation trigger Reduced augmentation timing	$t_{lead} = 2y$

Chapter 3: Melbourne water supply system model and validation

The conceptual model created of the Melbourne water supply system simulates the system head works, plus Cardinia Reservoir, to meet demand allocated to three zones: Cardinia, Sugarloaf, and "the rest" as described in Figure 6. The key computational steps in the model are:

1. Determine storage in all reservoirs.
2. At the start of December, the model checks whether restrictions should be applied based on the active storage available and determines what the restriction level and associated savings are. For simulations comparing this model with REALM, the savings are applied to the variable component of demand for 12 months from implementation. For the RCC analysis an overall saving from restrictions was specified based on advice from the Steering Committee. The application of restrictions through specified modelling arrangements are discussed below.
3. At the start of January, the model checks whether a desalination order needs to be placed and what volume that order is, as per Table 7. The desalination is distributed equally over the following 12 months (i.e. April to March). The desalination plant operating arrangements are discussed further below. The need for North-south pipeline transfers in accordance with Table 7 are also determined at this point and distributed equally across the year.
4. To calculate the RCC, augmentation decisions are also checked at the start of January.
5. Demands are then determined based on the hydrological realisations, using standard Melbourne Water demand modelling, and on the restrictions level.

With known demands, the water balance simulation for the monthly timestep often the decision involves the notion of an "active" available water volume, which is the starting storage, plus inflows, less any evaporation, passing flow, other environmental flow and dead storage. Water allocated from any of the storages is always limited by the residual demand for the relevant part of the system; that is total demand less any water already supplied from elsewhere, recalling that demand is split between Cardinia Reservoir, Sugarloaf Reservoir and the remainder of the system. The entire sequence of decisions is described in Appendix 2.

The characteristics of the reservoirs are described in Table 8 below.

Table 8: The characteristics of the Melbourne water supply system reservoirs

Storage / Harvesting Point	Capacity (ML)	Dead Storage (ML)	Target Operating Storage (ML)	Transfer Capacities (ML/d)	Environmental Releases (ML/m)	Share of Inflows	Demand	Net evap'n
Cardinia Reservoir	268,485	139,223	241,636	To Silvan: 350	152 (5ML/d)	N/A	21.7% less Tarago	Modelled
Greenvale Reservoir	Not represented, assumed to be at 90% storage. Average net evaporation removed (from Upper Yarra) each month.							
Maroondah Reservoir	22,000	3,250	N/A	190	30.4 (1ML/d)	100%, Spill rule used	n/a	Assumed zero
O'Shannassy Reservoir	3,100	1,200	N/A	270	Min (inflow, 243)	100%	Available harvest	Assumed zero
Silvan Reservoir	Not represented, assumed to be at 90% storage				2ML/d (Modelled by subtracting from UY Trib harvesting)	Average net evaporation removed (from Upper Yarra) each month.		
Sugarloaf Reservoir	96300	21500	N/A	WTP capacity: Min: 170 Max: 560	0	N/A	26% or 10.66% if S≥0.93	Modelled
Tarago Reservoir	37600	4000	N/A	WTP capacity: Min: 20 Max: 70	Smaller of 5ML/d or inflow	94% (6% loss)	16650 or 9990 if S>0.93	Modelled
Thomson Reservoir	1023000	158870	N/A	1400	Passing flows at 3 points downstream as per bulk entitlement – add 20ML/d for operating allowance, VEWH = 10,000/12 + 0.039*inflow	94% (6% to SRW)	n/a	Assumed zero
Upper Yarra Reservoir	185000	70700	110000	To Silvan: 1380, reduced by tributary harvesting	10ML/d plus 17GL/a (VEWH– can't be pumped)	100	Remaining demand	Modelled
Upper Yarra Tribs & Coranderrk	N/A	N/A	N/A	Ideal Diversion Factor	Ideal Diversion Factor	Ideal Diversion Factor	Available harvest	Assumed zero
Yan Yean	30200	11900	N/A	WTP capacity: 155	1Ml/d (0.2 ML/d, Stage 2+ restrictions)	100		Modelled
Yering Gorge Pump Station	N/A	N/A	N/A	Pumping relationship	See bulk entitlement – add 20ML/d for operating allowance	Pumping relationship	n/a	n/a

Treatment of thresholds in RCC simulations

The simulations are based on a 20 year model. Over this 20 year modelling period, the metropolitan water corporations would revise desalination action points, or trigger storages, every five years when Urban Water Strategies are updated. Therefore, for simulations quantifying the reliability cost curve, trigger thresholds for desalination orders, restrictions, etc were varied to reflect changes in demand. This was done as follows. The thresholds in Table 6 were first converted to a storage time, τ, using:

$$\tau = \frac{\beta * S_{cap}}{\bar{D} - Q_{desalCap}} \quad (7)$$

where the annual demand and the desalinisation capacity were measured at the start of the period. As demand and installed capacity changed throughout the simulation, the triggers were recalculated by rearranging the above equation. These calculations always assume an average year i.e. no adjustment of demand due to weather. This approach enables adjustments to the operating arrangements as the system and demand changes and maintains a constant threshold in terms of equivalent time reserve. For example, stage 1 restrictions occur are triggered when the amount of water in storage could supply approximately 4 years demand with no inflows and the desalination plant running continuously at capacity.

Hydrological assumptions

The base case set out in Table 6 will be examined under two different sets of hydrological realisations. These expectations are stochastically generated synthetic streamflows based on the historic inflow patterns. One set will be based on the past forty years of inflows while the second will be based on the past twenty years. The two sets of hydrological realisations are referred to as Post 75 and Post 97 respectively. Essentially the assumptions behind these two scenarios are that we expect inflows to be statistically like the last 40 years (Post 75) or like the last 20 years (Post 97).

For both the Post 75 and Post 97 expectations, 10,000 different twenty year hydrological realisations were generated. Some high level statistics for the streamflow sequences are shown in Table 9. Note that the values in this table are for the total inflows in streams accessed by Melbourne Water harvesting sites, with the exception of the Thompson river where the Melbourne Water share (94 per cent of total streamflow) is used. Many of these harvesting sites rely on pumping or diversion to an aqueduct or pipeline and it is not physically possible to harvest the higher flows at those points.

Table 9: Statistical characteristics of synthetic streamflows

	Post 75	Post 97
Inflow Wettest Sequence (GL/a)	1,219	926
Mean Inflow (GL/a)	875	700
Standard Deviation (GL/a)	286	209
10 Percentile Inflow Sequence (GL/a)	773	629
Inflow Driest Sequence (GL/a)	570	489
Driest 10 year Inflow Sequence (GL/a)	477	400
Driest year (GL/a)	155	160

The Post 97 event is referred to in DELWP's climate change guidelines as the Stepped Change scenario. This scenario is used by Melbourne Water in formulating its annual VDP water order technical advice.

Stochastic inflows were generated using the Wathnet 5 software. The stochastic model is a multi-site, multi-season, multi-state contemporaneous autoregressive model. The model represents relationships between sites, variations across the year and includes first order autoregression. The inflow scenarios used to train the stochastic model were supplied by Melbourne Water and are similar to scenarios previously used by Melbourne Water, with some update of the data for recent conditions. The RCC simulations were based on 10,000 replicates, each 50 years long.

Validating the model of Melbourne's water supply system

To ensure that the conceptual model of Melbourne's water supply system sufficiently accurately replicates the outputs of Melbourne Water's REALM model, it has been compared to a range of REALM simulations. A series of eight evaluation scenarios have been used. This evaluation involved Melbourne Water generating a series of REALM runs and the conditions of those runs being replicated within the MatLab model, referred to as Melbourne-RCC. The test cases were as follows.

- A period of 50 years was used.
- Simulations began at the observed storage levels at the start of 2017.
- Simulations all used the medium growth demand scenario supplied by Melbourne Water for the period 2017-2066.
- Four inflow scenarios based on 1967-2016 were used: historic, return to dry, post 75 and post 97, as supplied by Melbourne Water.
- Restrictions were imposed which depend on the inflow scenario. Restriction decisions were made based on the start of December storage.
- For each inflow scenario, the system was simulated with and without desalination. Annual desalination orders were determined based on the storage at the start of April.

A series of standard figures were produced, along with a set of standard statistics. Annual result figures are shown for the entire system, along with the monthly storage comparisons for the whole system in Figure 12 through Figure 27. Silvan and Greenvale Reservoirs are not explicitly modelled, and it was assumed that they were maintained at 90 per cent of their capacities at all times.

Figures 12 through 27 incorporate statistics comparing REALM and the conceptual model. For water supplied the bias only exceeds 1 per cent for one case – the highly stressed return to dry with no desalination scenario. The Nash-Sutcliff coefficient of efficiency for annual water supplied exceeds 0.8 for nearly all cases, the exception being Return to Dry with desalination. System outflows also generally agree very well. Looking at the results from system storage time series, it is evident that there are some systematic offsets between the two models for periods of time these are relatively minor from a research perspective.

In many of the scenarios, individual years where there is a marked difference in water supplied or in systems outflows are evident. These are associated with times when storage is close to a threshold at a decision-making time for restrictions, desalination orders or spills. They typically come about because the two models implement a different level of restriction or one of the models has a significant spill somewhere in the system while the other does not. Along with similar differences in desalination orders, these individual years can result in a change in the sustained offset in storage between the two models. This behaviour is expected where there are thresholds in the system operation and are a symptom of uncertainty in the REALM and the conceptual model.

Overall, the comparisons indicate that the system dynamics are modelled similarly by the two models for a wide range of system conditions. This gives confidence in utilising the conceptual model for the stochastic simulations of the system that will form the basis of the remainder of this report.

The model calibration was confirmed by Melbourne Water and the model was accepted by the Steering Committee consisting of representatives from Melbourne Water, City West Water, Department of Environment Land Water and Planning, South East Water and Yarra Valley Water.

It is worth noting that it is challenging to achieve similar performance between different models where schematisation is completely different. Generalised model structures often do not capture interactions between components of the system, such as reservoirs and the transfer network. On this basis, the high degree of fidelity achieved with the conceptual model used in this report is important for the significance of its findings.

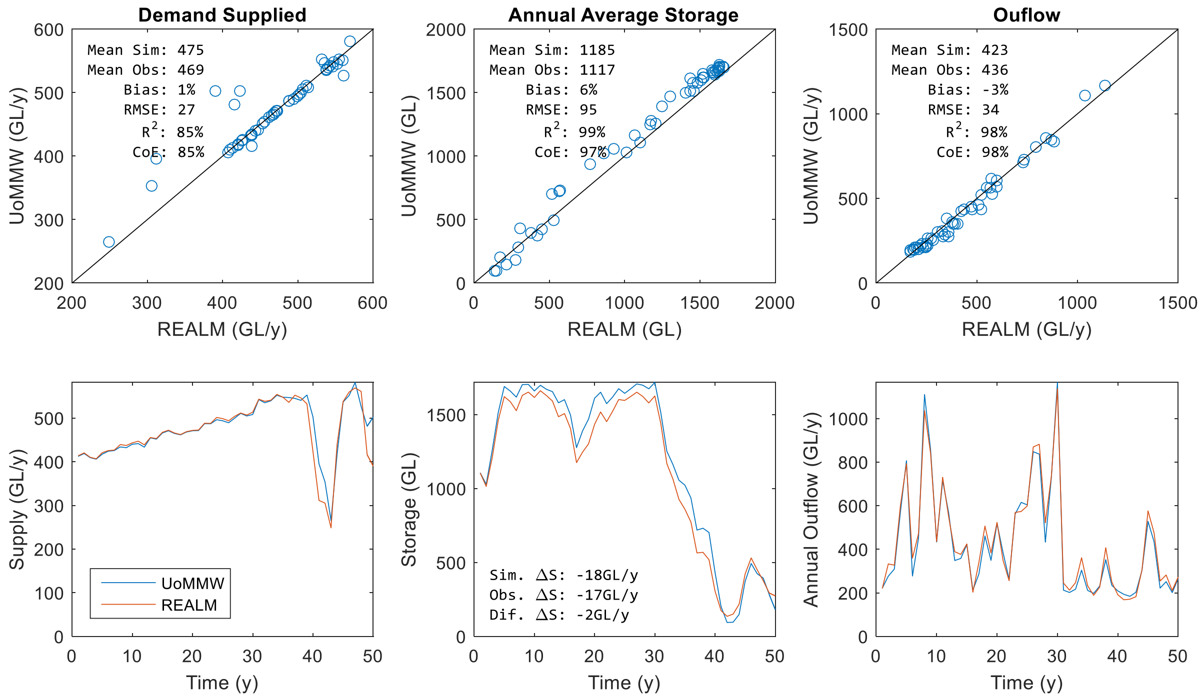


Figure 12: Annual comparison of REALM and the conceptual model simulations for the Historic Inflows and no desalination scenario.

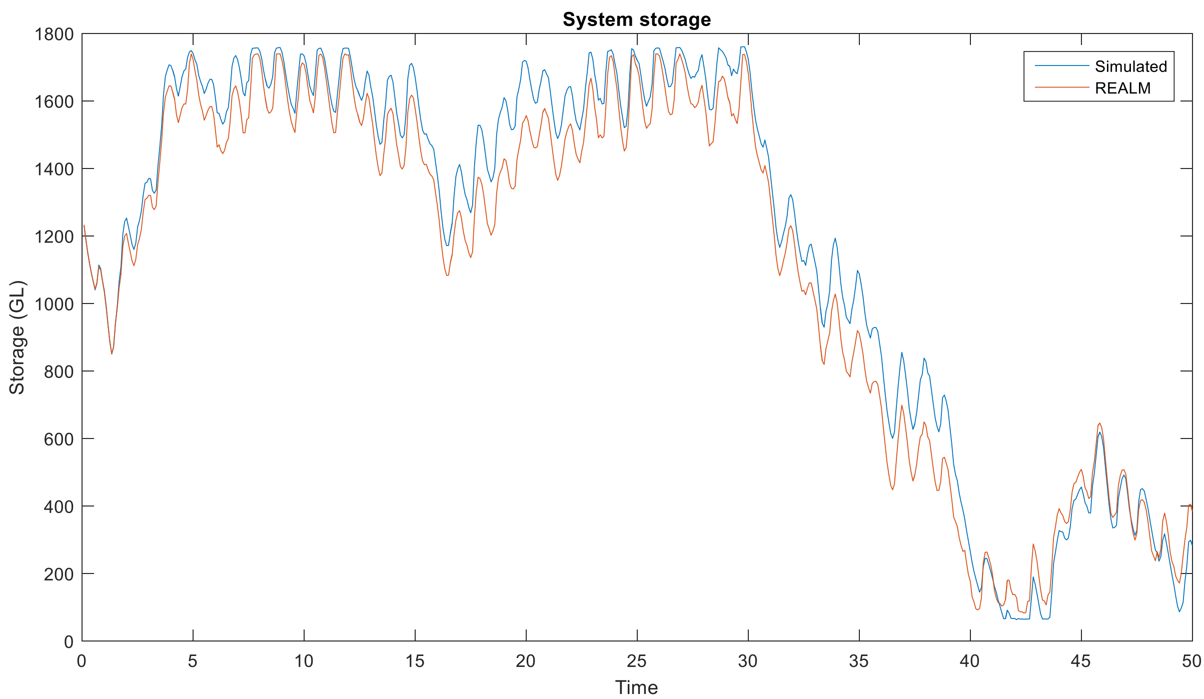


Figure 13: Comparison of Monthly REALM and simulated storage levels for Historic Inflows without desalination.

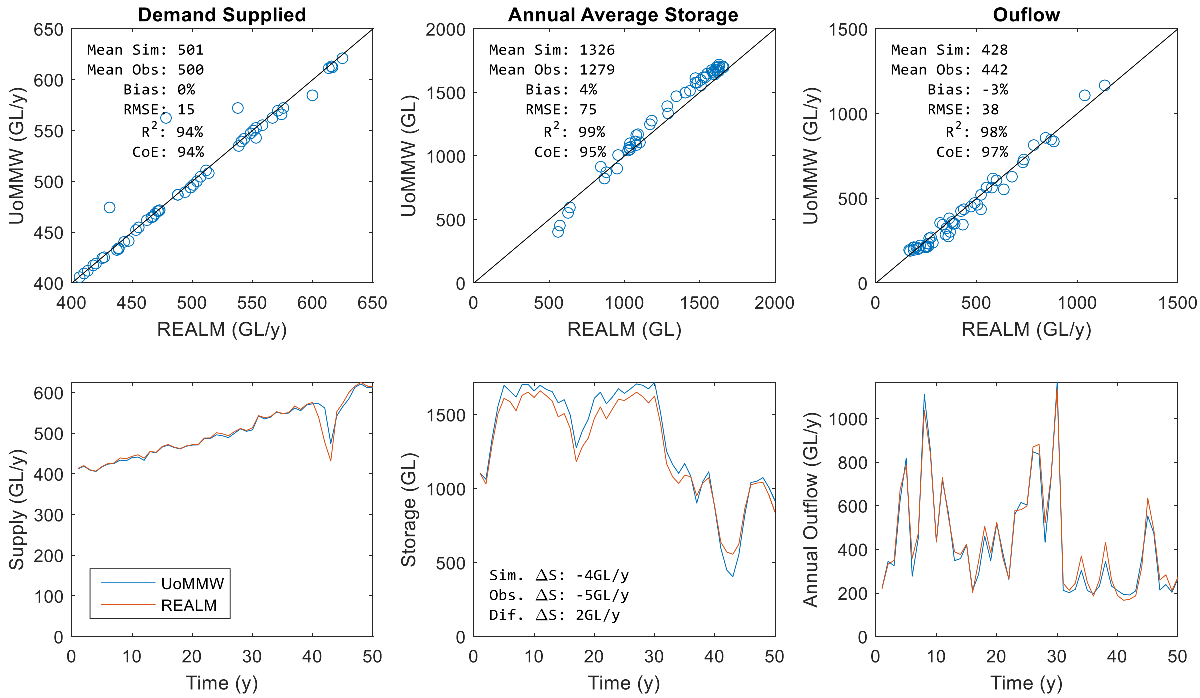


Figure 14: Annual comparison of REALM and the conceptual model simulations for Historic Inflows with desalination.

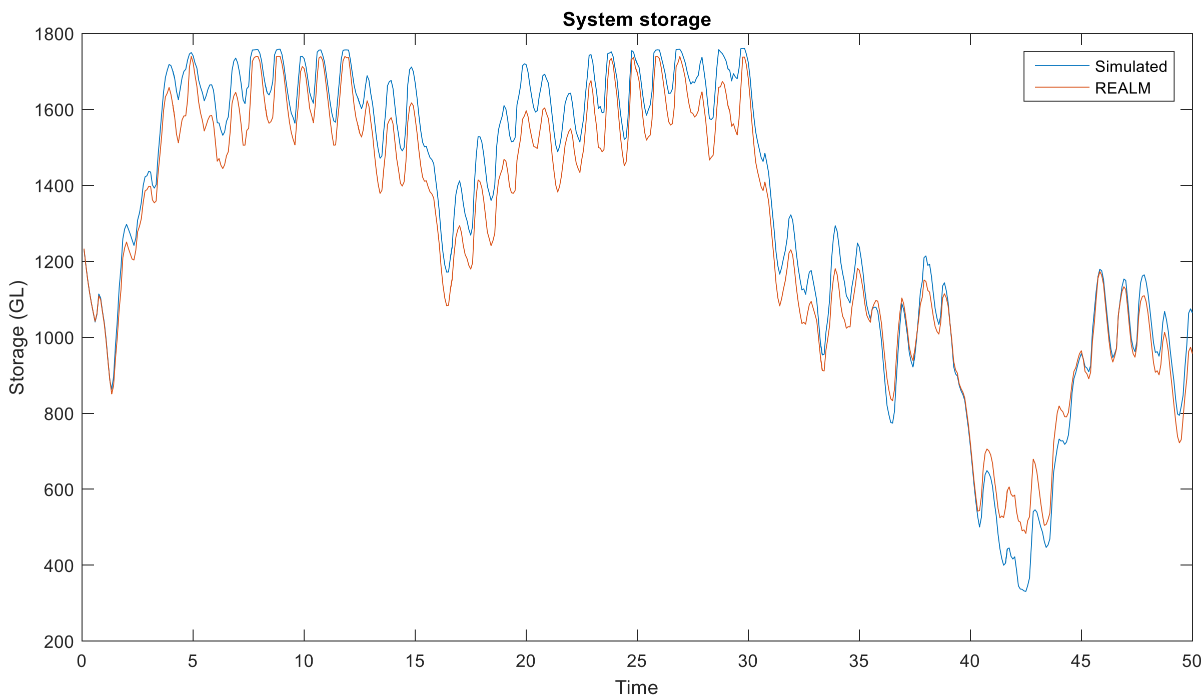


Figure 15: Comparison of Monthly REALM and simulated storage levels for Historic Inflows with desalination.

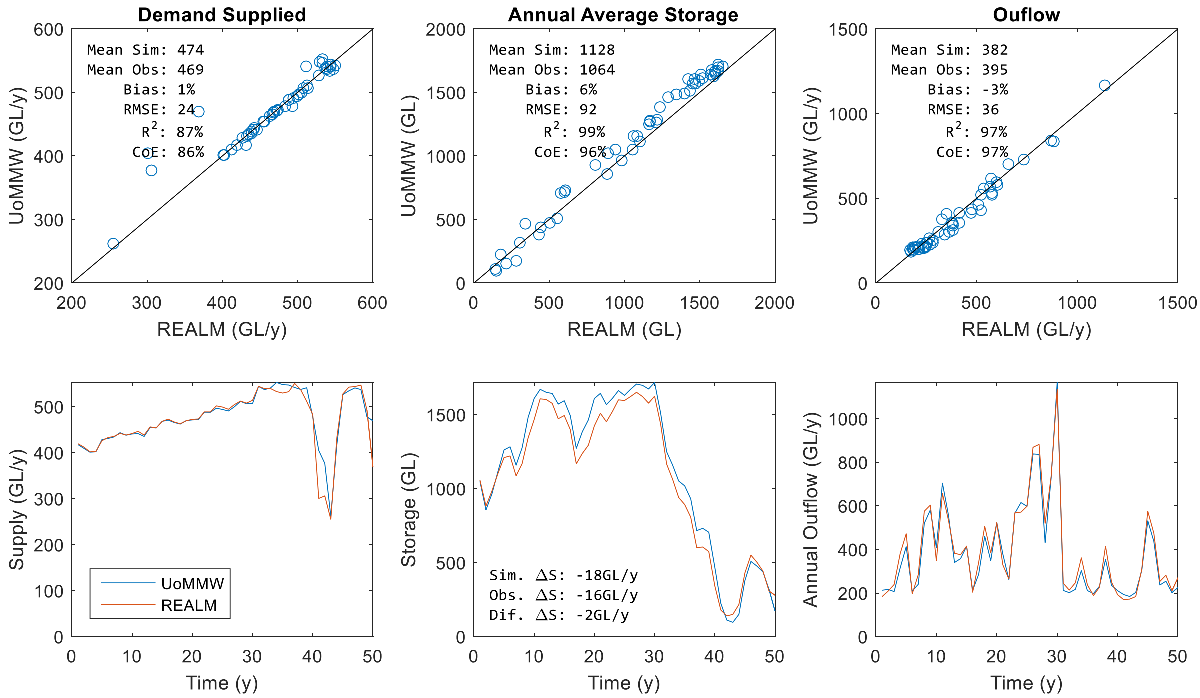


Figure 16: Annual comparison of REALM and the conceptual model simulations for Post 1975 Inflows without desalination.

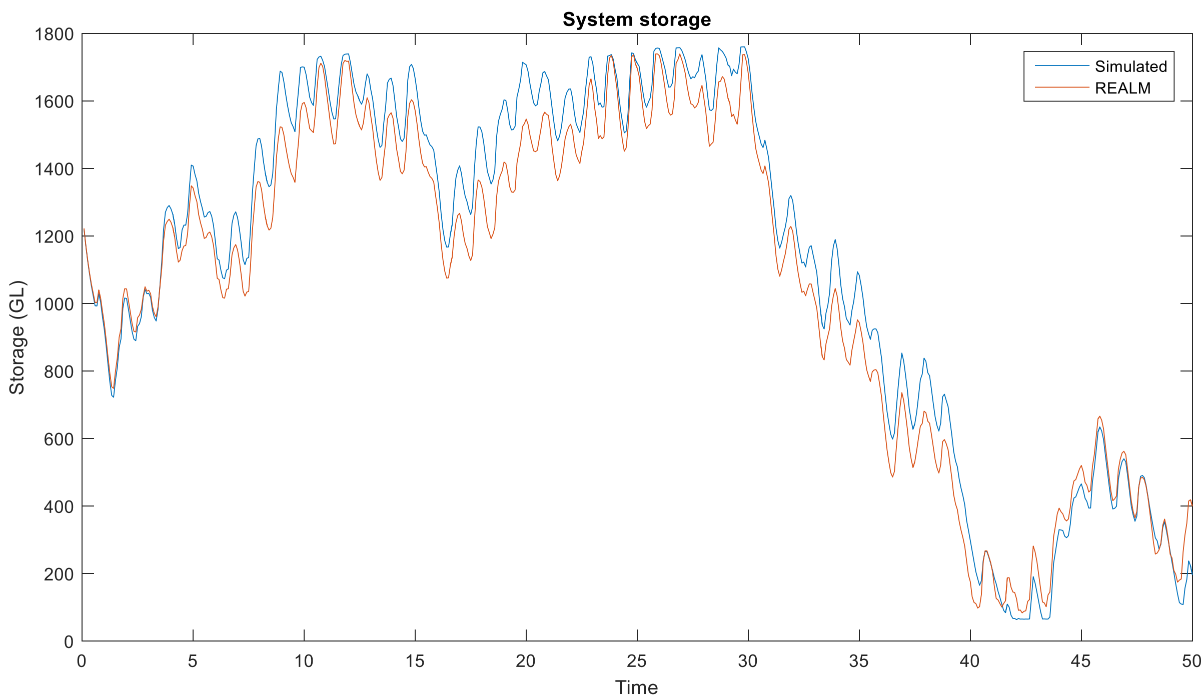


Figure 17: Comparison of Monthly REALM and simulated storage levels for Post 1975 Inflows without desalination.

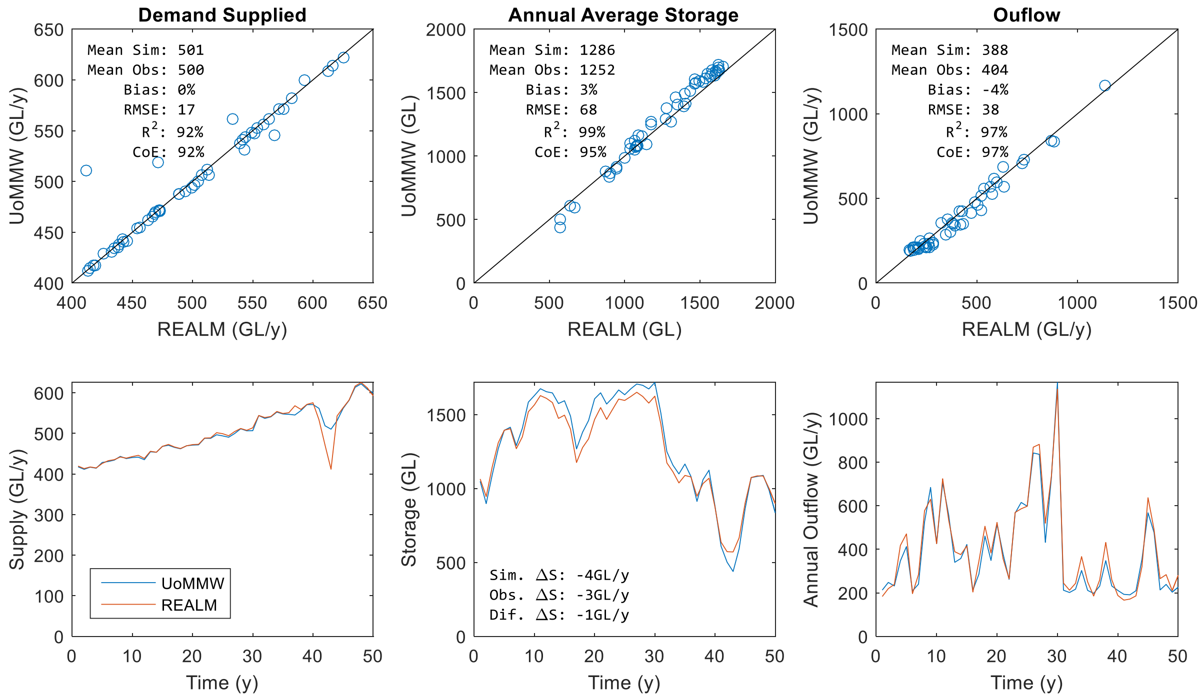


Figure 18: Annual comparison of REALM and the conceptual model simulations for Post 1975 Inflows with desalination.

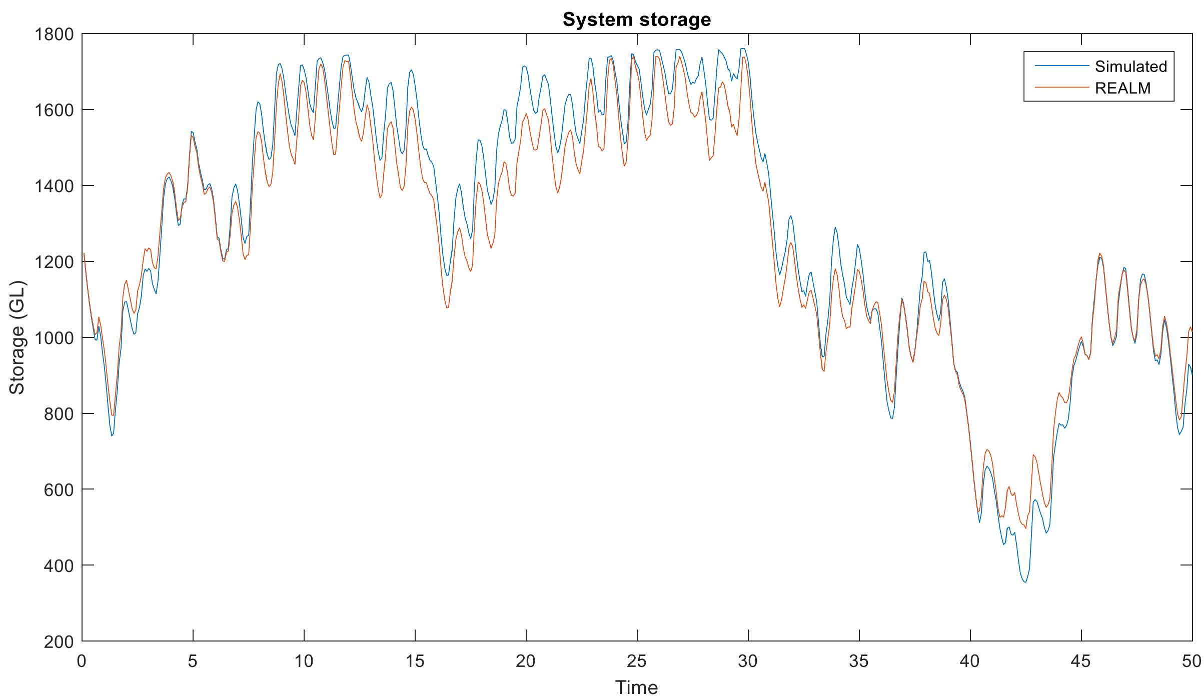


Figure 19: Comparison of Monthly REALM and simulated storage levels for Post 1975 Inflows with desalination.

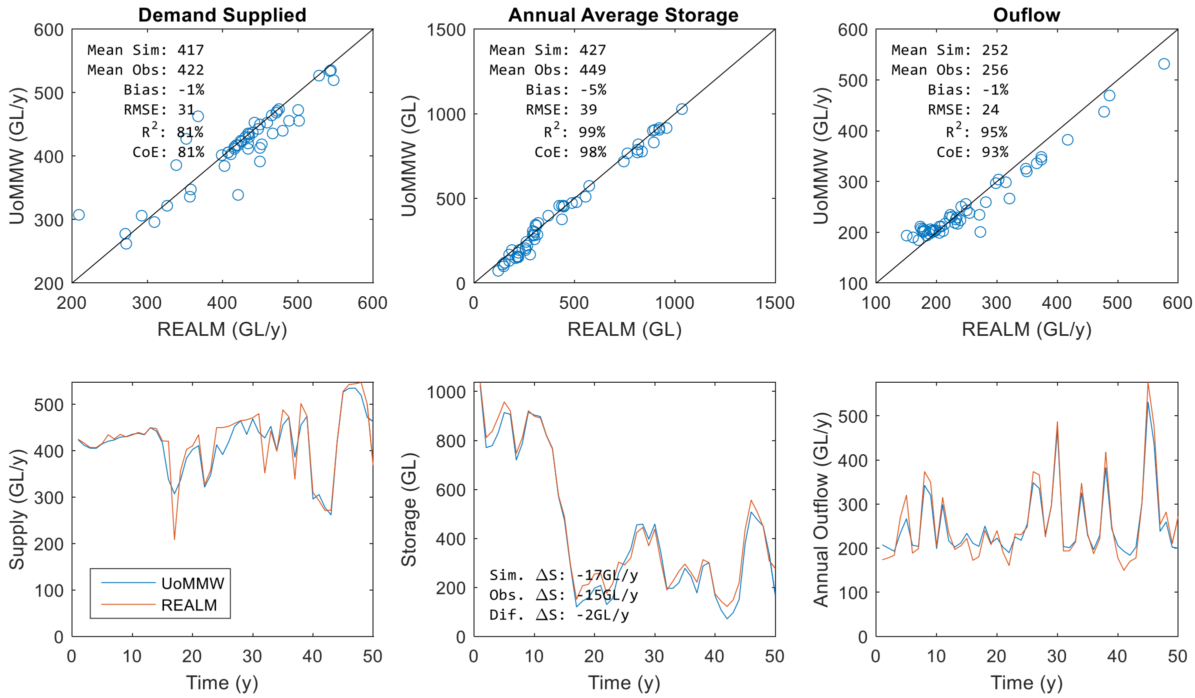


Figure 20: Annual comparison of REALM and the conceptual model simulations for Post 1997 Inflows without desalination.

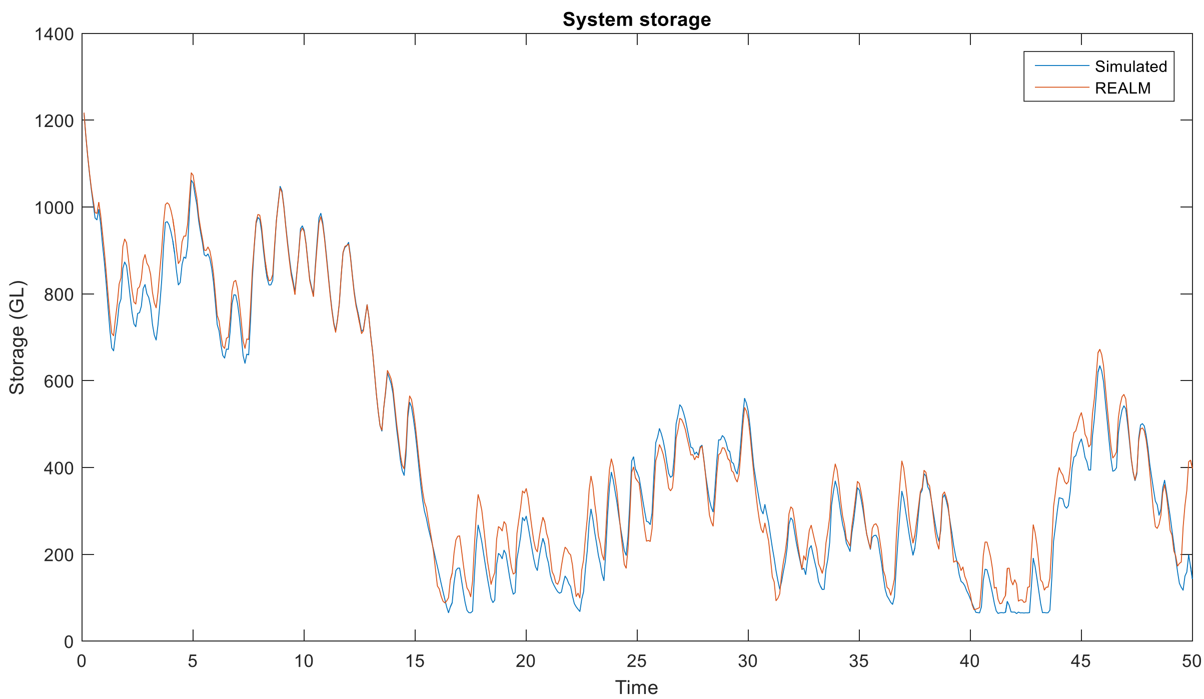


Figure 21: Comparison of Monthly REALM and simulated storage levels for Post 1997 Inflows without desalination.

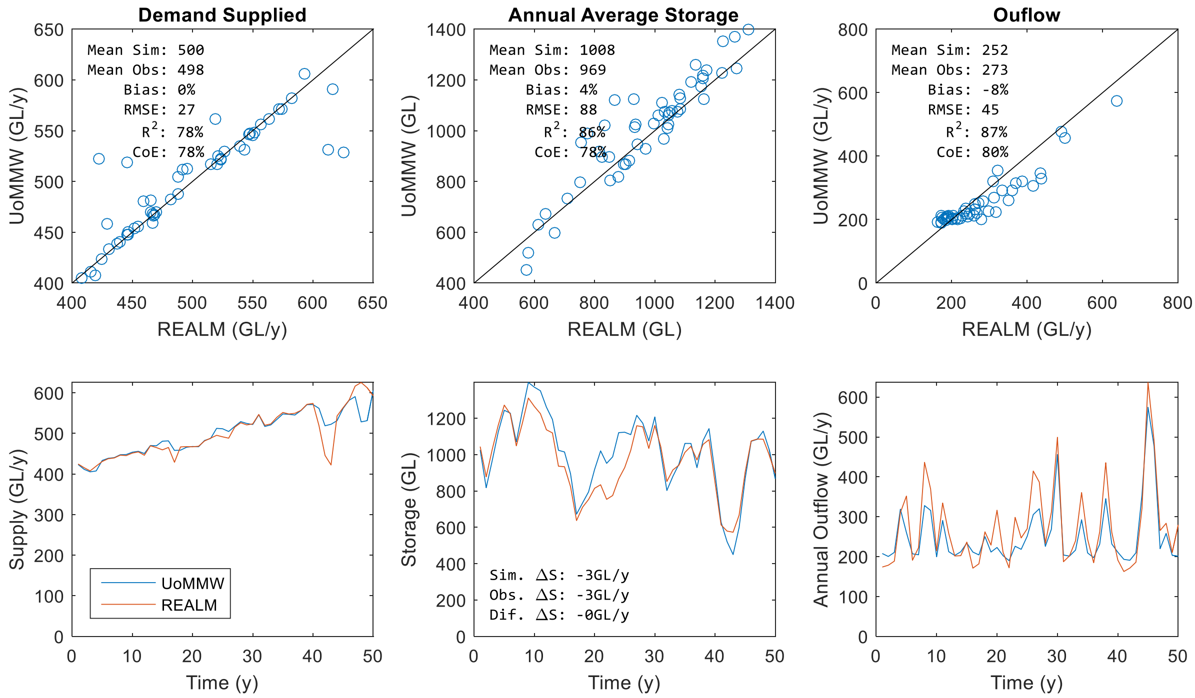


Figure 22: Annual comparison of REALM and the conceptual model simulations for Post 1997 Inflows with desalination.

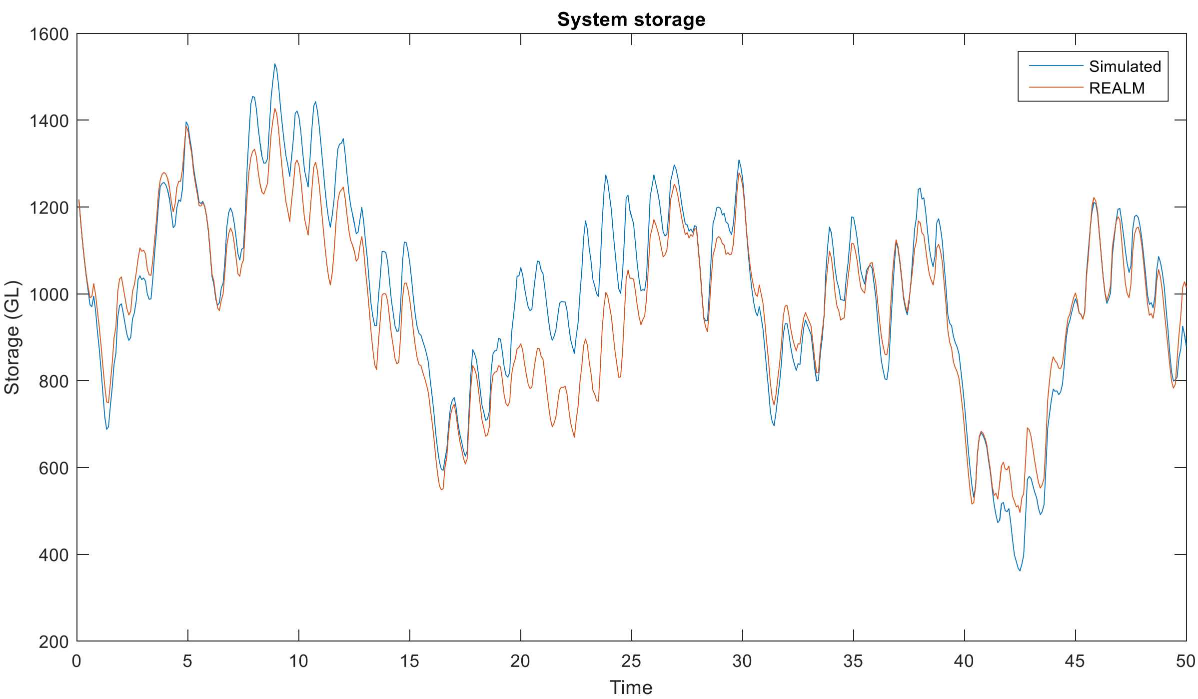


Figure 23: Comparison of Monthly REALM and simulated storage levels for Post 1997 Inflows with desalination.

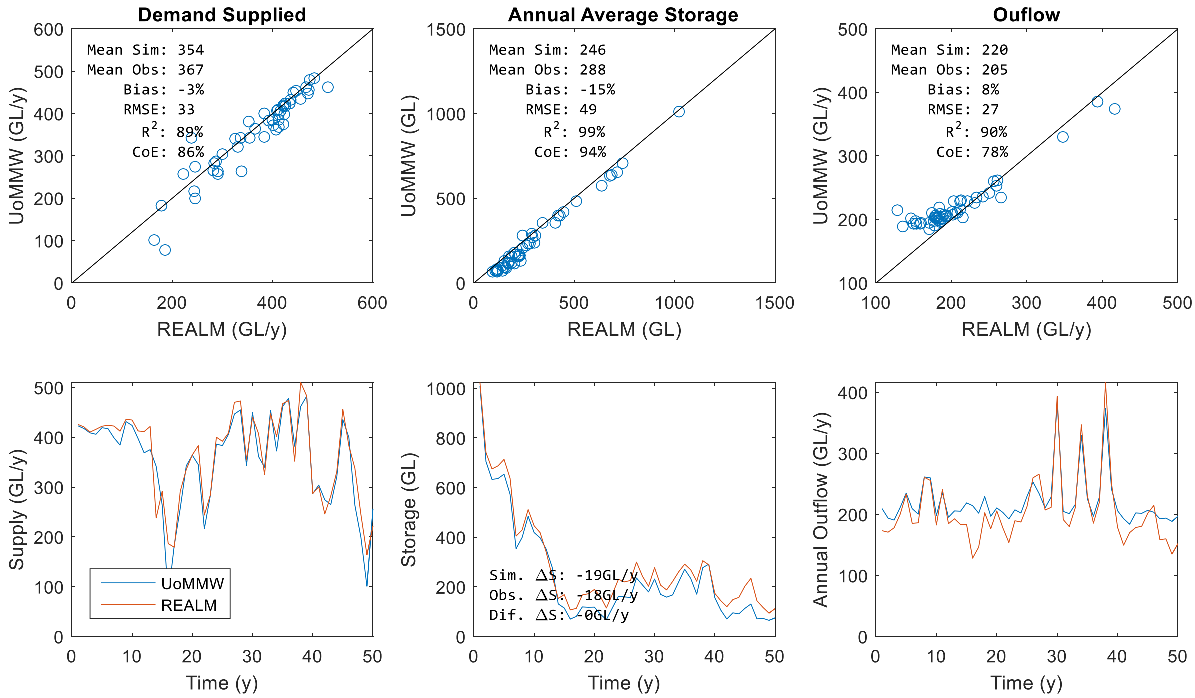


Figure 24: Annual comparison of REALM and the conceptual model simulations for Return to Dry Inflows without desalination.

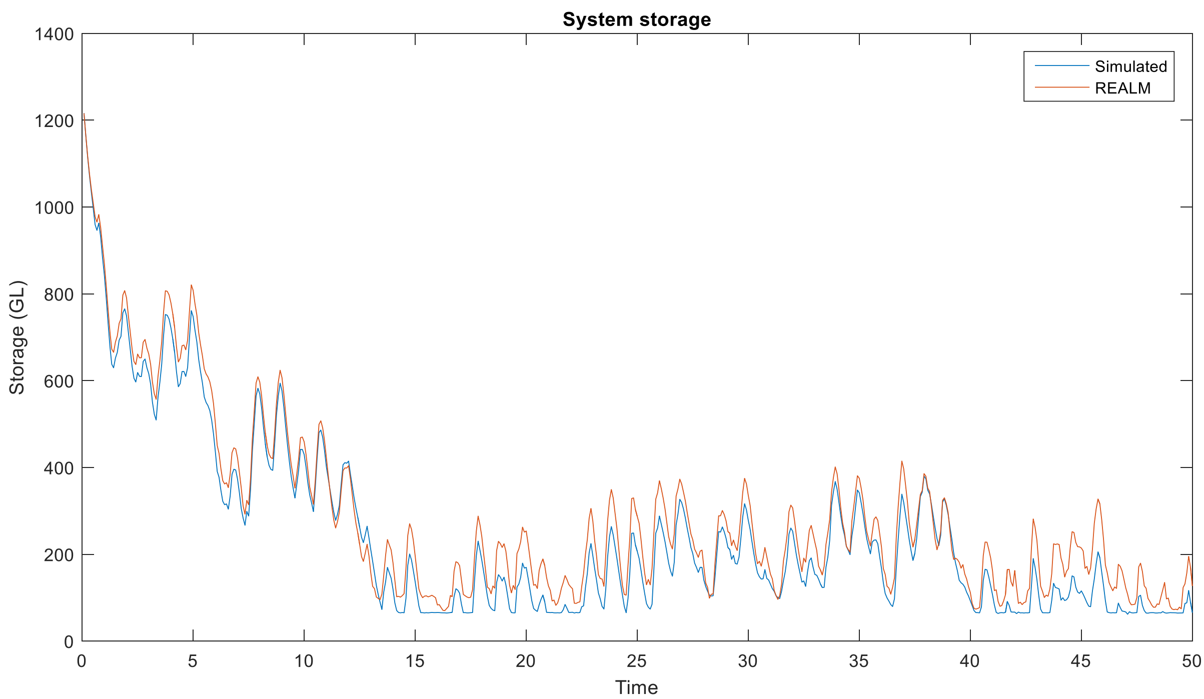


Figure 25: Comparison of Monthly REALM and simulated storage levels for Return to Dry Inflows without desalination.

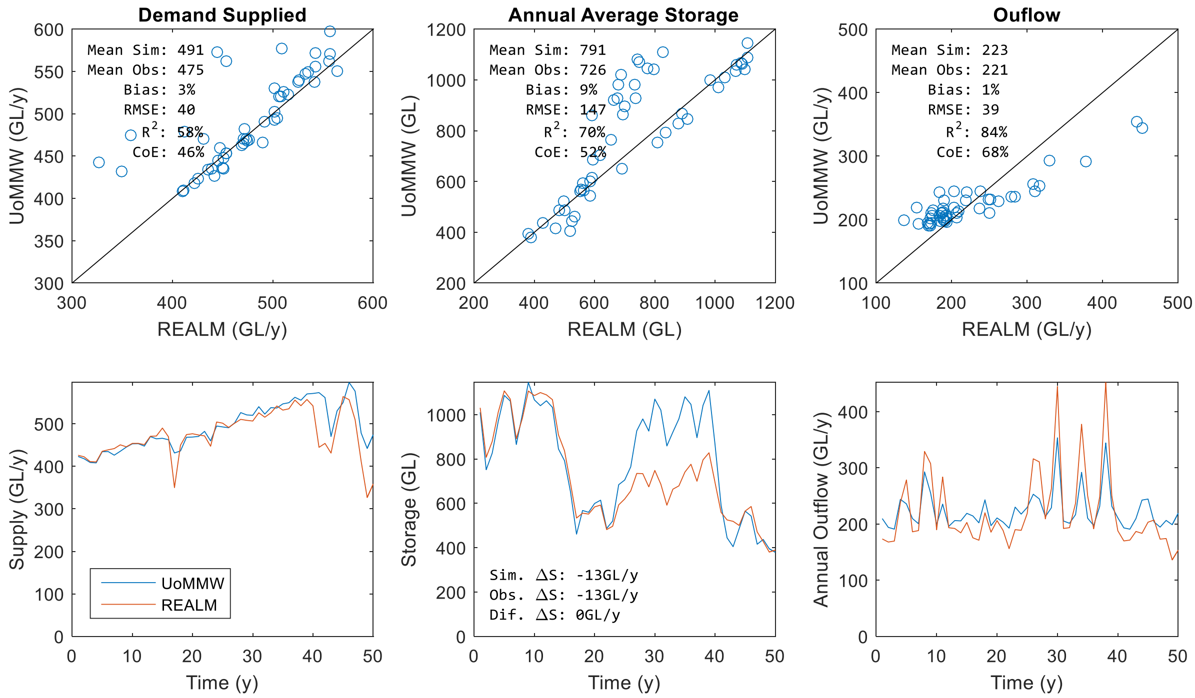


Figure 26: Annual comparison of REALM and conceptual model simulations for Return to Dry Inflows with desalination.

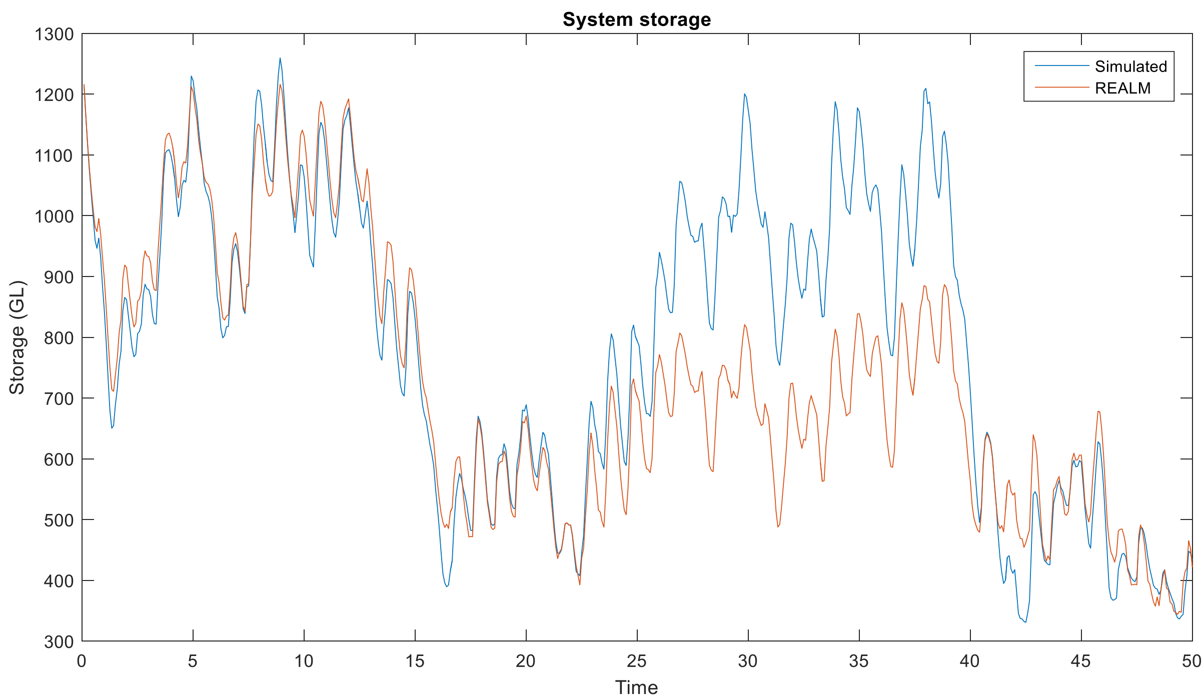


Figure 27: Comparison of Monthly REALM and simulated storage levels for Return to Dry Inflows with desalination.

Chapter 4: Base case cost of maintaining reliable water supply

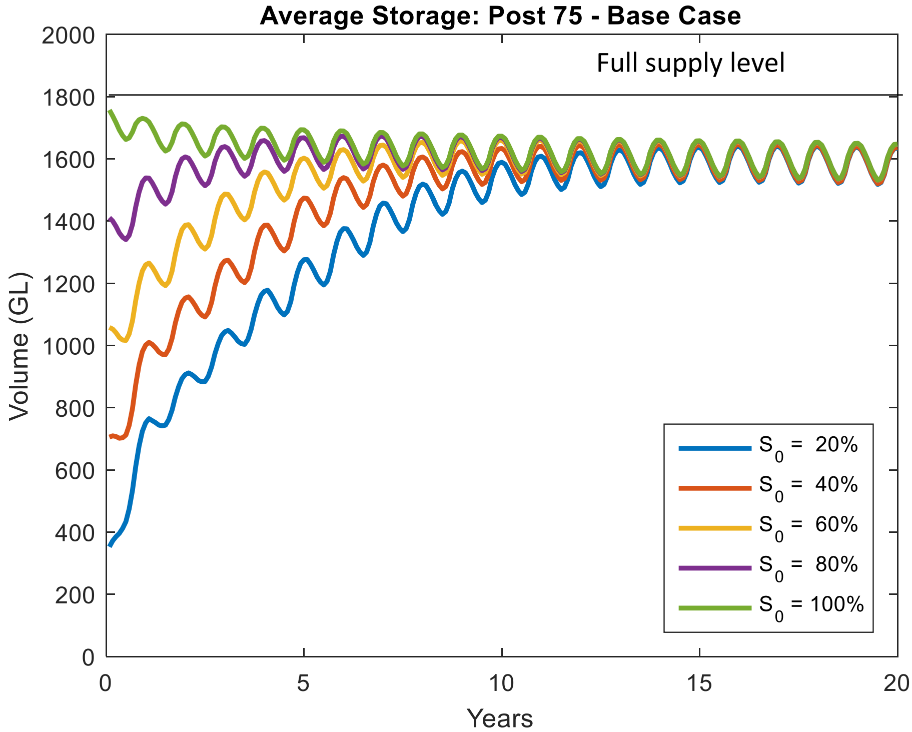
The base case uses a stochastically generated sequence based on either the historic inflows adjusted to reflect post 1975 conditions or one generated from a sequence adjusted to reflecting post 1997 conditions. These hydrological realisations can be considered to be representative of the last twenty years or the last forty years of the historic record.

The base case is presented here. Given model runs over twenty years long, the costs include (approximately in the order that they are triggered) and the operating costs associated with the VDP, associated pumping costs for water from the VDP, any costs associated with the restrictions regime, the capital costs associated with scenarios that lead to the need to augment the VDP, the capital costs with any additional desalination plants built after the expansion of the VDP, the pumping, treatment and opportunity costs associated with scenarios that seek to use water from the North-South Pipeline, plus any social costs that may be incurred in scenarios where it is not possible to meet Stage 4 restricted demand. There are a total of 10,000 simulations conducted for each base case. Results are generally presented as average behaviour across the 10,000 inflow realisations.

Storage behaviour

The least costly way to meet target demand is to use gravity fed reservoirs. However, in situations with low storage, it is necessary to take other actions to maintain water security. The modelling decision to use the VDP, or other sources of water, is based on either the level of water in storage (for desalination and restriction decisions) or on the level of water in storage and hydrological expectations (for augmentation decisions). Consequentially, the level of water in storage drives the costs associated with meeting the target demand. Figure 28 shows the average storage behaviour over time of the base case for a range of initial storages, from 20 per cent through to 100 per cent full and for the Post 75 and Post 97 inflow scenarios. In the Post 97 case, the VDP is used significantly and the adjustment of the order threshold associated with additional capacity due to the plant being augmented is clear of the initial storages of 20 and 40%. In these cases, the decision to expand the VDP is made at the start of the simulation due to the storage level. The different inflow cases have different long-term average storage levels (approximately 1600GL for Post 75, and approximately 1400GL for Post 97) because the overall inflows to the system (stream inflow plus desalination) vary and the extra desalination in Post 97 is smaller than the reduction in streamflow in Post 97 compared with Post 75.

Figure 29 shows the occurrence of restrictions and shortfalls (being unable to supply Stage 4 restricted demand) for the Post 75 and Post 97 inflow scenarios. With the chain of augmentations simulated, this indicates that the system is able to provide secure supply across the 20 year simulation horizon. There are essentially zero shortfalls, below stage 4 restricted demand, occurring in these simulations and stage 4 restrictions are rare, except when initial storages are at 40 per cent. Stage 3 restrictions occur in 7 per cent of runs (sometimes for 2 years) in the Post 97 scenario. For stage 1 and 2 restrictions, note that the simulations actually commence with stage 2 restrictions, given the initial storage level of 40% and the system is able to recover from that situation through augmentation (which is also always triggered at the start of the simulation for a 40 per cent initial storage). With higher initial storage conditions the occurrence of low level restrictions is much rarer. This gives reasonable confidence on the overall system resilience provided that augmentations are able to be implemented to meet the assumptions defined in the model and simulations (eg lead time and trigger level).



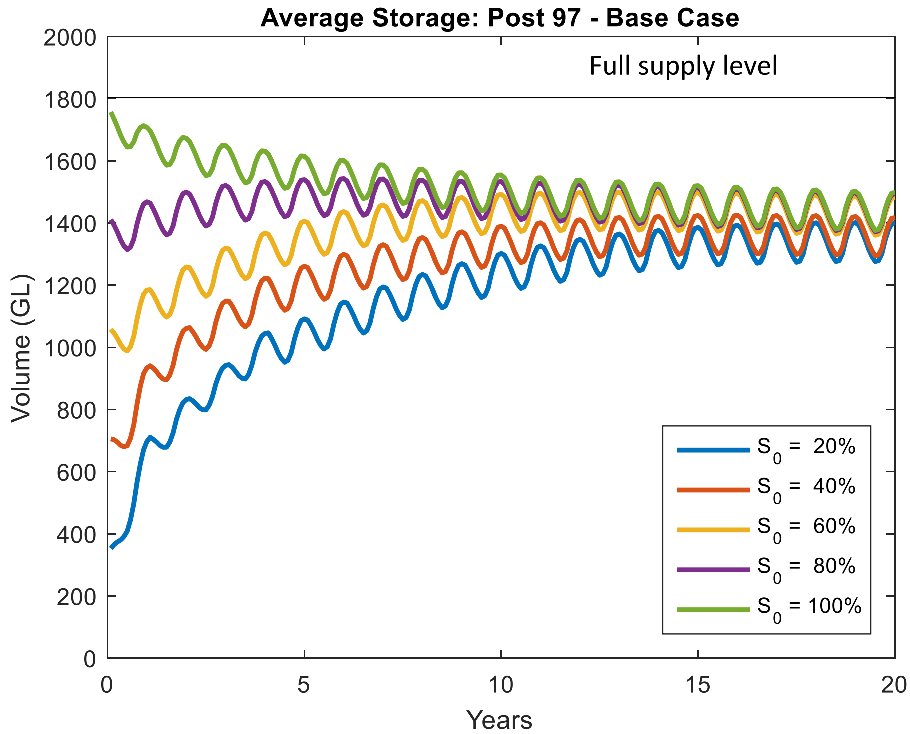


Figure 28: Storage behaviour, Post 75 Base case, Initial storages ranging from 20 to 100 per cent.

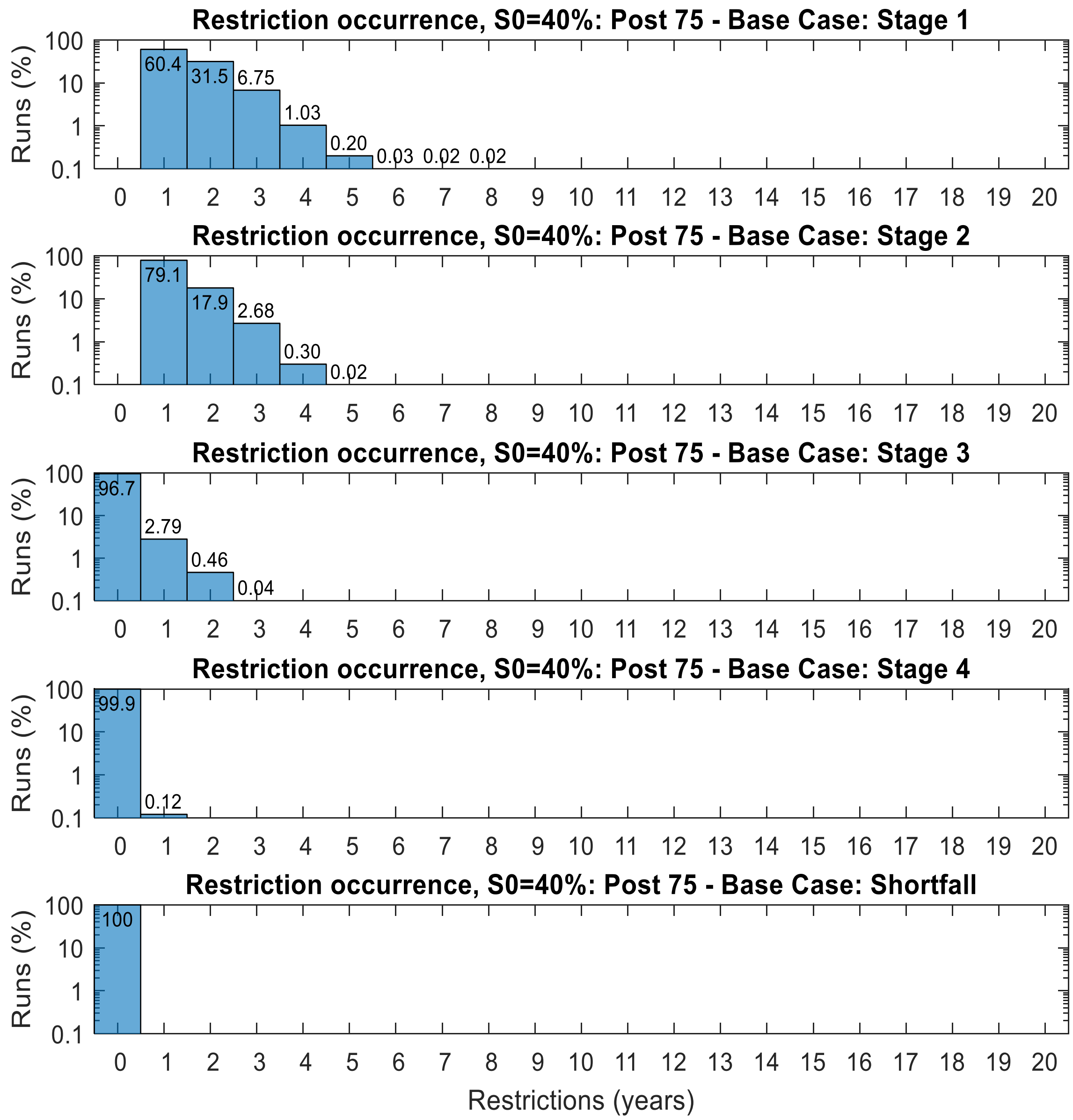


Figure 29: Occurrence of restrictions (top 4 panels) and shortfalls below stage 4 restricted demand for the Post 75 and Post 97 Base case for initial storages of 40 per cent.

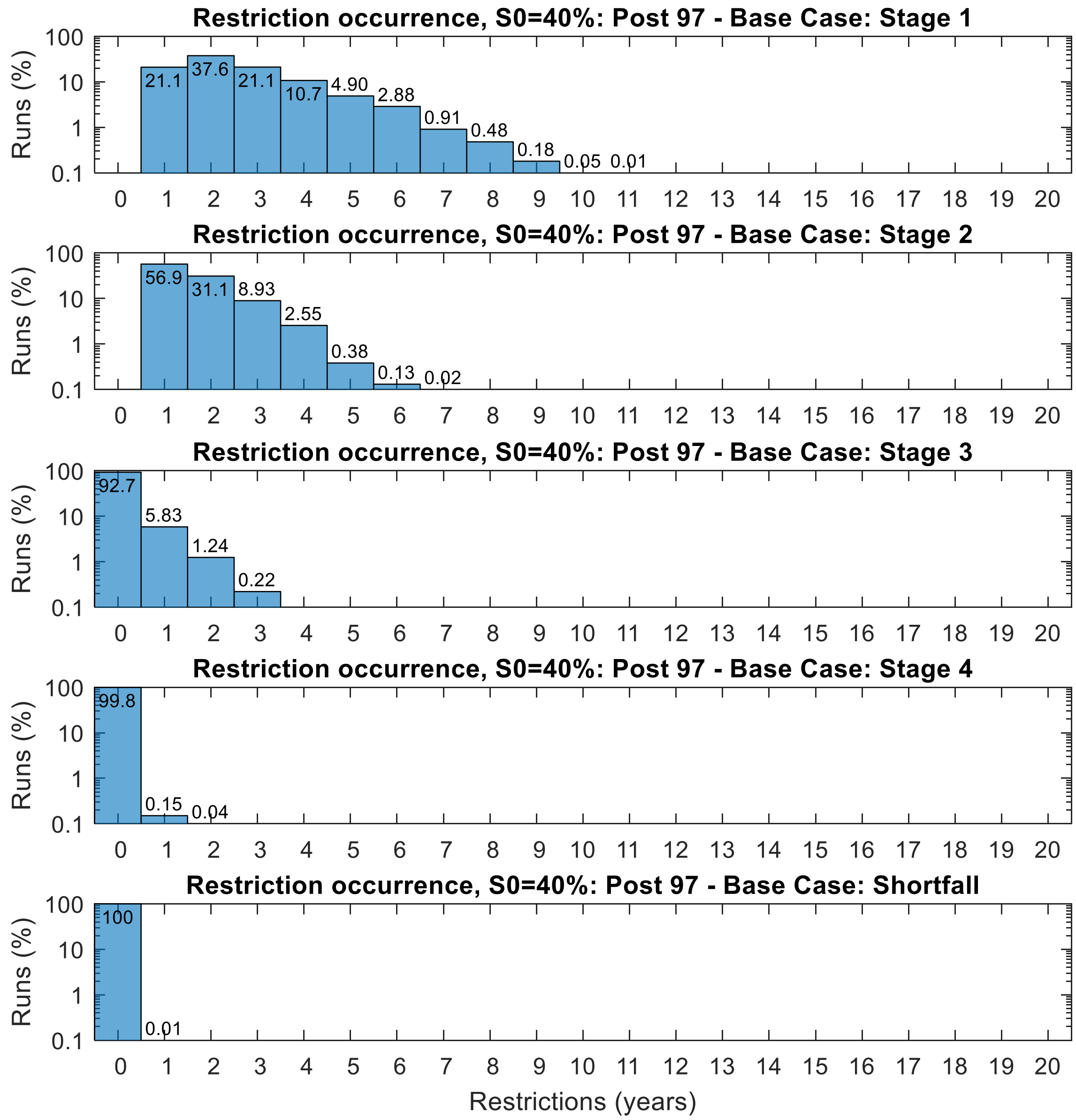


Figure 29 continued: Occurrence of restrictions (top 4 panels) and shortfalls below stage 4 restricted demand for the Post 75 and Post 97 Base case for initial storages of 40 per cent.

Component Costs for the Reliability Cost Curves

The costs associated with maintaining a reliable water supply are broken down into their individual components.

VDP Operating Costs

Under the base case, the first cost associated with maintaining a reliable water supply is operating the VDP at Wonthaggi. The operation of the desalination plant in the model is triggered when storages reach 65 per cent, as described in Table 6. These costs are primarily associated with operating the VDP; however, there are also costs associated with pumping water from Silvan to Cardinia. Figure 30 shows the net present value of the VDP operation costs over the next 20 years as a function of initial storage while Figure 31 shows similar results for pumping water from Cardinia Reservoir to Silvan Reservoir, which is require under higher desalination rates due to insufficient demand at Cardinia. The Silvan pumping costs are relatively small, approximately 2.5 per cent of the total cost involved in operating the VDP. However, they are still approximately 7 per cent of the water order cost and provide incentives to order small volumes of desalinated water more frequently rather than larger volumes of desalinated water less frequently.

The modelling highlights that desalination operation costs increase slowly as S_0 decreases from 100 per cent because operation of the desalination plant becomes more likely. More rapid increase occurs below 65 per cent when water is ordered from the start of the simulation. Stage 2 restrictions are triggered at 50 per cent storage and the savings due to increases in restrictions leads to a pause in the increase in desalination costs as S_0 moves from 55 per cent to 50 per cent. This is partially due to eh operating arrangements defined in the base case, described in Table 6. For S_0 < 40 per cent desalination operation costs (and Silvan pumping costs) increase more rapidly due to the augmented desalination plant (triggered for S_0<55 per cent).

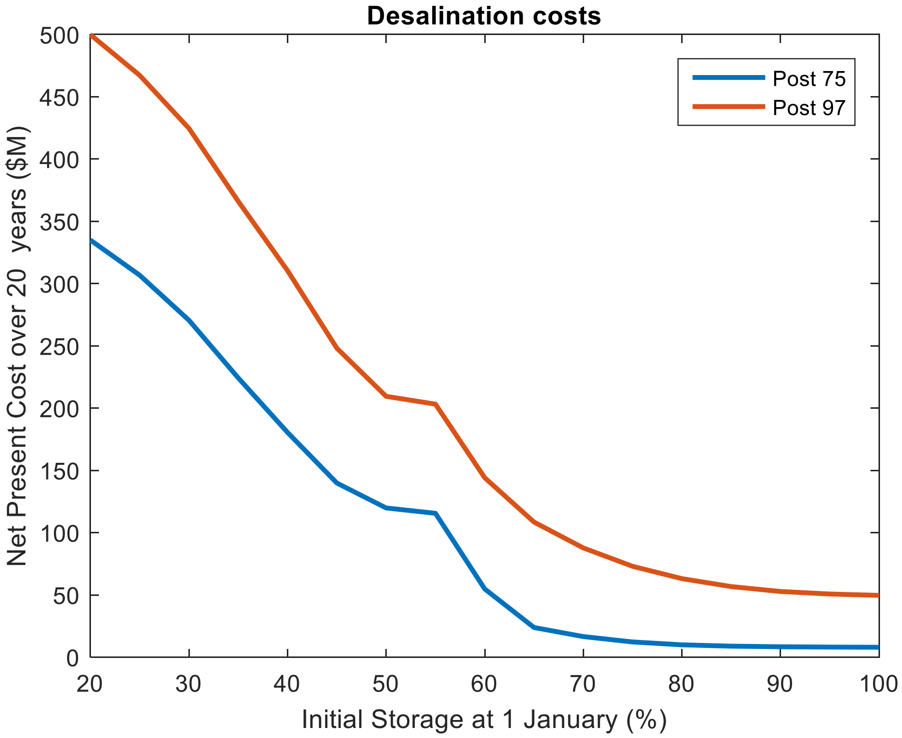


Figure 30: Desalination costs, Post 75 and Post 97 Base case.

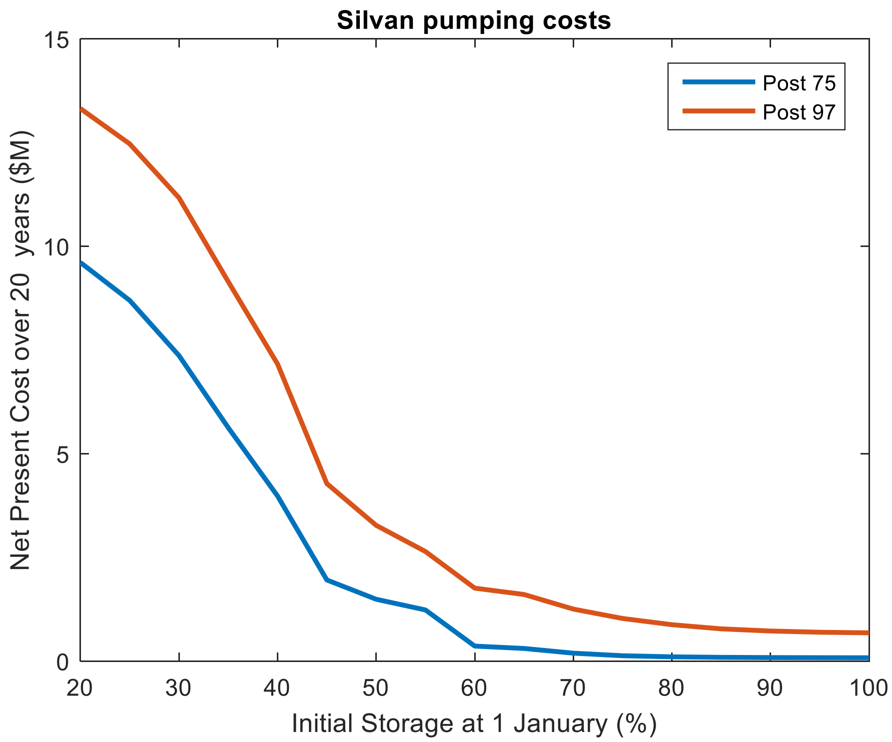


Figure 31: Silvan pumping costs, Post 75 and Post 97 Base case.

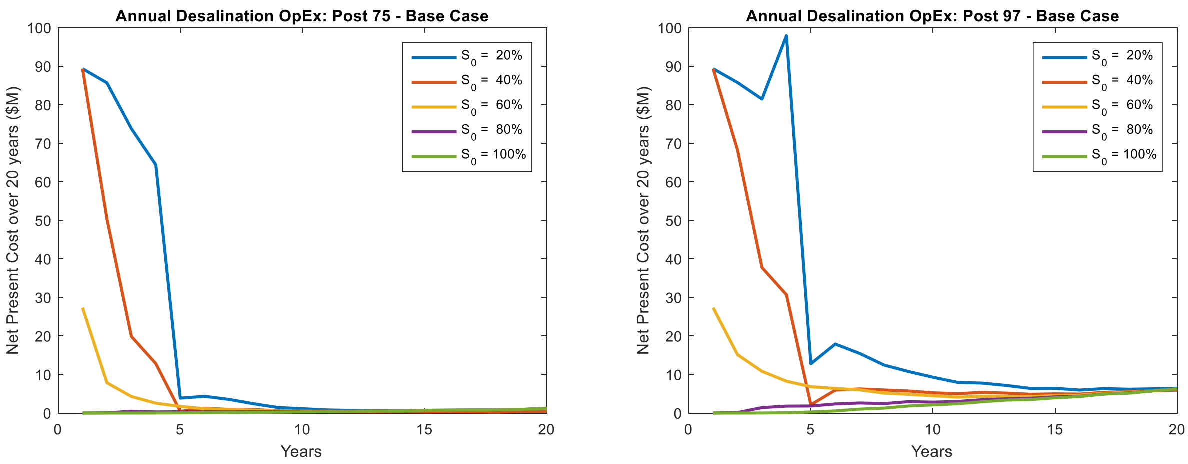


Figure 32: Annual desalination costs, Post 75 and Post 97 Base case.

Figure 32 shows the changes in annual desalination operation costs over the 20 year simulation. It plots the costs incurred in operating the VDP, and any additional augmentations, over the twenty years simulated for different initial storages. For S_0 of 60 per cent or less, most of the costs are in the early years as desalination orders are made at the start of the simulation (that is when December storage is below 65 per cent) and the system gradually recovers. For S_0 of 80 per cent and 100 per cent, desalination operation costs gradually increase over time as the demand on the system grows, especially for the Post 97 case.

Modelling of augmentations of Melbourne's water supply system

The timing of any expansion of the water supply system is important to the time and probability discounted costs associated with maintaining a reliable water supply system. For this study, when storages are below about 50 per cent, as described in Table 6, then the expansion of the VDP is triggered. At levels about 50 per cent initial storages, there is a possibility that the augmentation will be triggered but it declines according to the hydrological realisation and the starting storage. Figure 33 and Figure 34 show histograms of expansions of the VDP arising from the base case for different starting storages for the Post 75 and Post 97 streamflow scenarios. It should be noted that modelling highlights the need for an additional desalination plant in a significant number of the Post 97 realisations. The timing of all augmentations is described in more detail in Chapter 7.

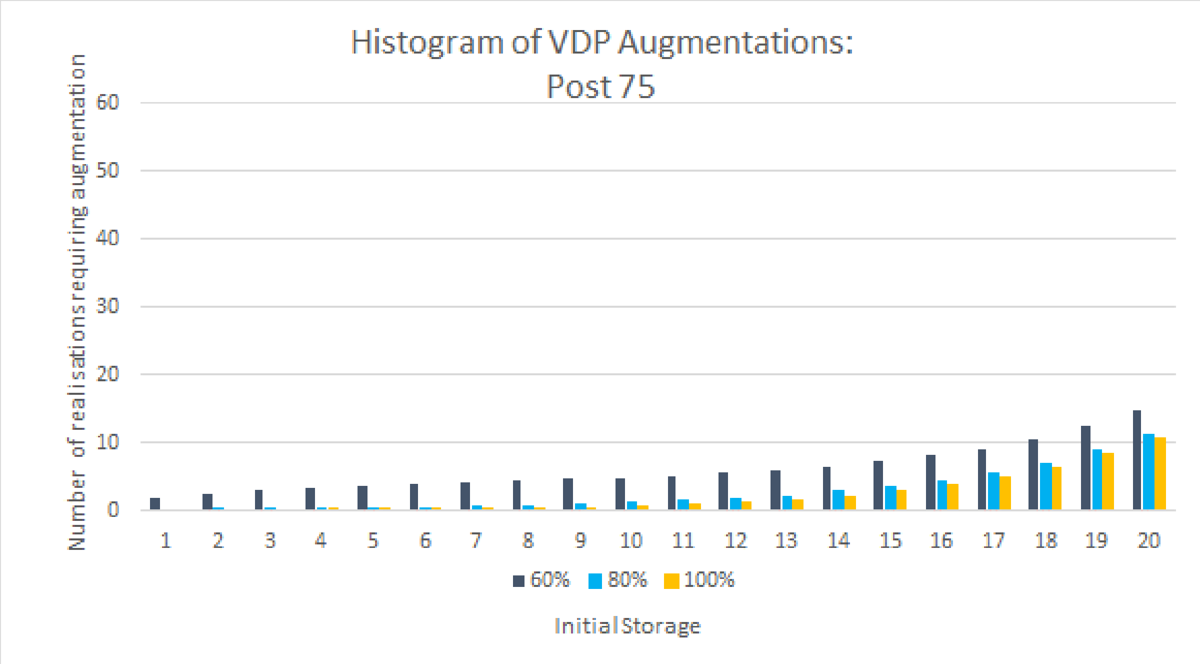


Figure 33: Augmentation of the VDP, number of realisations based on initial storage, Post 75 Base case.

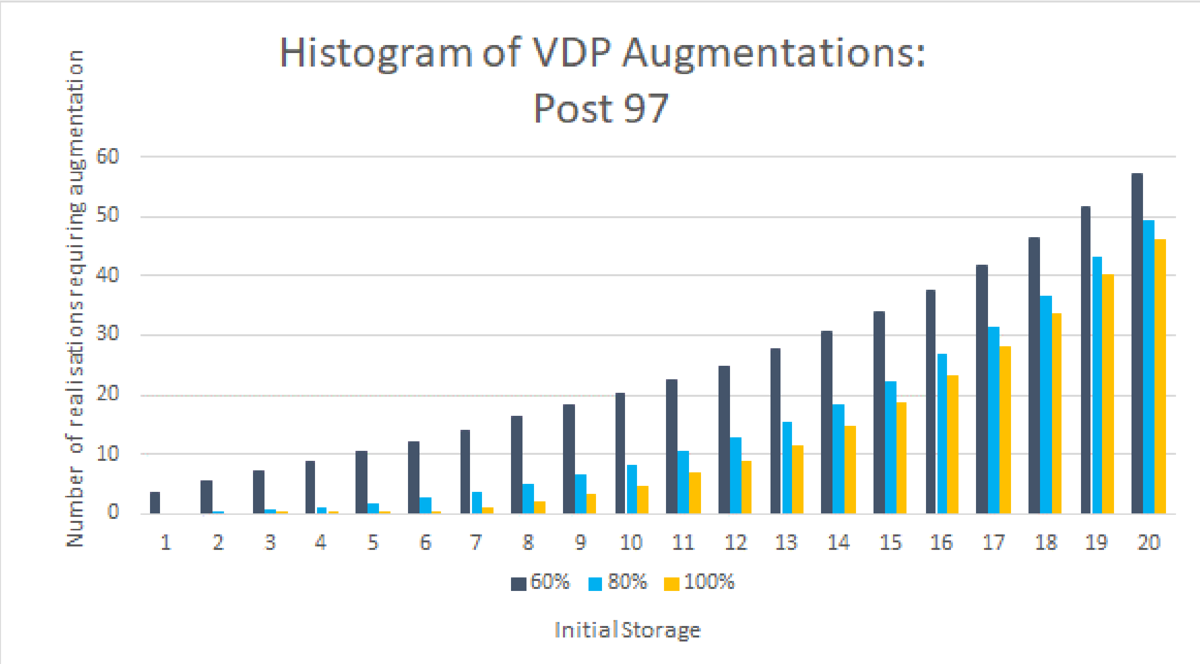


Figure 34: Augmentation of the VDP, number of realisations based on initial storage, Post 97 Base case.

Capital costs from modelling

The capital costs of desalination are the time and probability discounted costs associated with the need within the model to expand the VDP, build a new desalination plant and then expand it further. They are incurred separately when the augmentation trigger storage levels are reached. The decisions for the second and third augmentations cannot be made until the previous augmentation is operating. The combined capital costs are described in Figure 35, which represents the probability and time discounted costs associated with the augmentations described in Figure 33 and Figure 34.

In the post 75 scenario, the capital costs start at a relatively low level, reflecting the fact that there are just two augmentations over the first four years, when the initial storage are completely full, and a total of 239 by the end of the twenty-year planning period. However, this is out of a total of 10,000 hydrological realisations. As such, it represents a low probability event. The probability gradually rises as S_0 decreases from 100 per cent to around 55 per cent. While the trigger level changes as the expected demand increases due to population growth, it is at approximately 55 per cent storage that the expansion is triggered in each simulation of the water supply system, which means augmentations are triggered immediately (i.e. for all 10000 realisations) when $S_0 \leq 50\%$, accounting for the sharp increase in capital costs.

In the Post 97 scenario, the probability of triggering an augmentation is higher, and they happen sooner in the simulation due to lower stream inflows in these realisations. As a consequence, when initial storages are completely full there are 250 times more augmentations than in the Post 75 hydrological realisations, resulting in correspondingly higher capital costs. As the initial storage level decreases from 100 per cent, the probability of an augmentation being triggered increases Figure 48 shows. The probability of requiring an additional expansion of the water supply system also increases. The result is that the capital costs of the RCC reach $1 billion when the initial storages are 20 per cent.

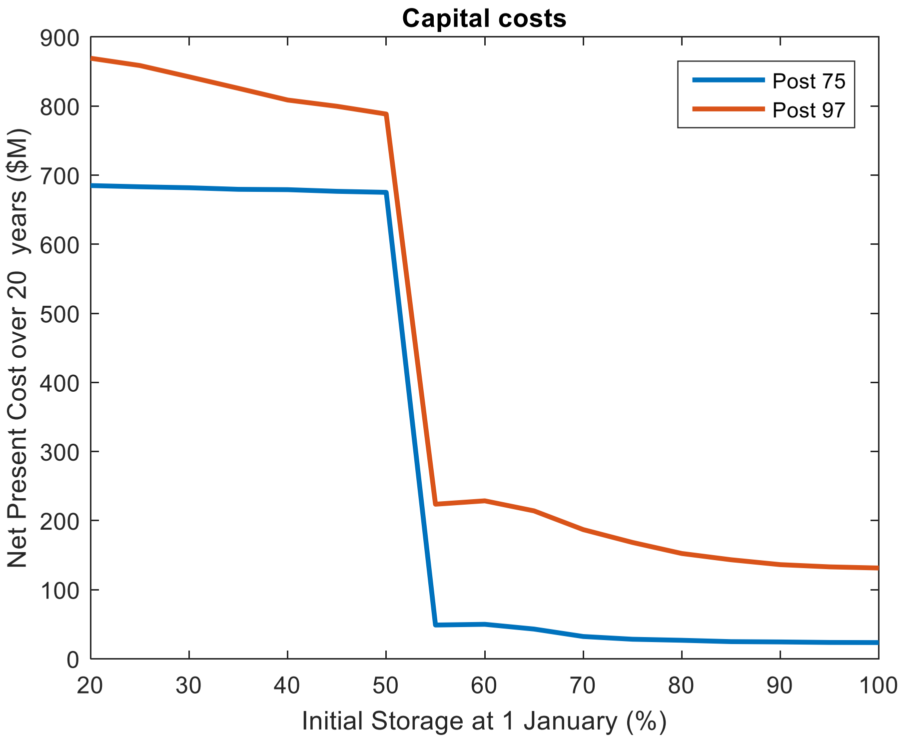


Figure 35: Augmentation costs, Post 75 and Post 97 Base case.

Costs of restrictions

The social costs associated with imposing restrictions over the twenty-year modelling horizon are described for Melbourne's water supply system in Figure 36. This figure applies the social costs associated with restrictions, described in Table 3, with the frequency with which they are imposed, described in Figure 29. For simulations based on the Post 75 hydrology, if the water supply system is initially full then storages rarely fall so that restrictions are imposed. In contrast, in the Post 97 simulations, restrictions are imposed in some realisations even when the initial storage is at 100 per cent. In addition, when storages are low, the social costs of restrictions are higher in the Post 97 simulations as they are imposed for a longer period of time. As a consequence, the social costs of restrictions have net present value of almost $425 million when initial storages start at 20 per cent in the Post 97 base case compared with almost $350 million for the same initial storage in the Post 75 base case.

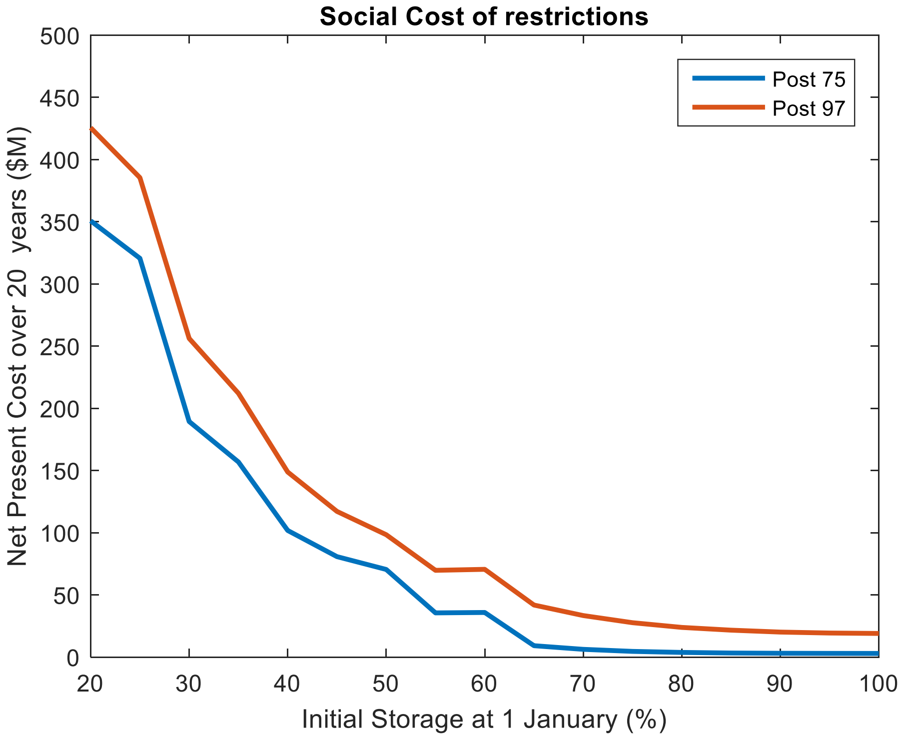


Figure 36: Social cost of restrictions, Post 75 and Post 97 Base case.

Modelled North-South Pipeline costs

In the base case, water is accessed from the North-South Pipeline when storages are at 30 per cent, consistent with the Statement of Obligations (System Management, 2016). This limits the contribution that the North-South Pipeline can make to underpinning Melbourne's water supply reliability and the cost contribution to the RCC. Modelling shows that the North-South Pipeline provides a benefit to Melbourne under the existing arrangements. The benefit is that it reduces the magnitude and frequency of social costs associated with not meeting Stage 4 restricted demand. There is limited difference between the Post 75 and Post 97 cases for the Base scenario as the pipeline is generally only operated early in the simulation in conjunction with large desalination orders. After the system recovers, the north-south pipeline is rarely used in the base scenarios.

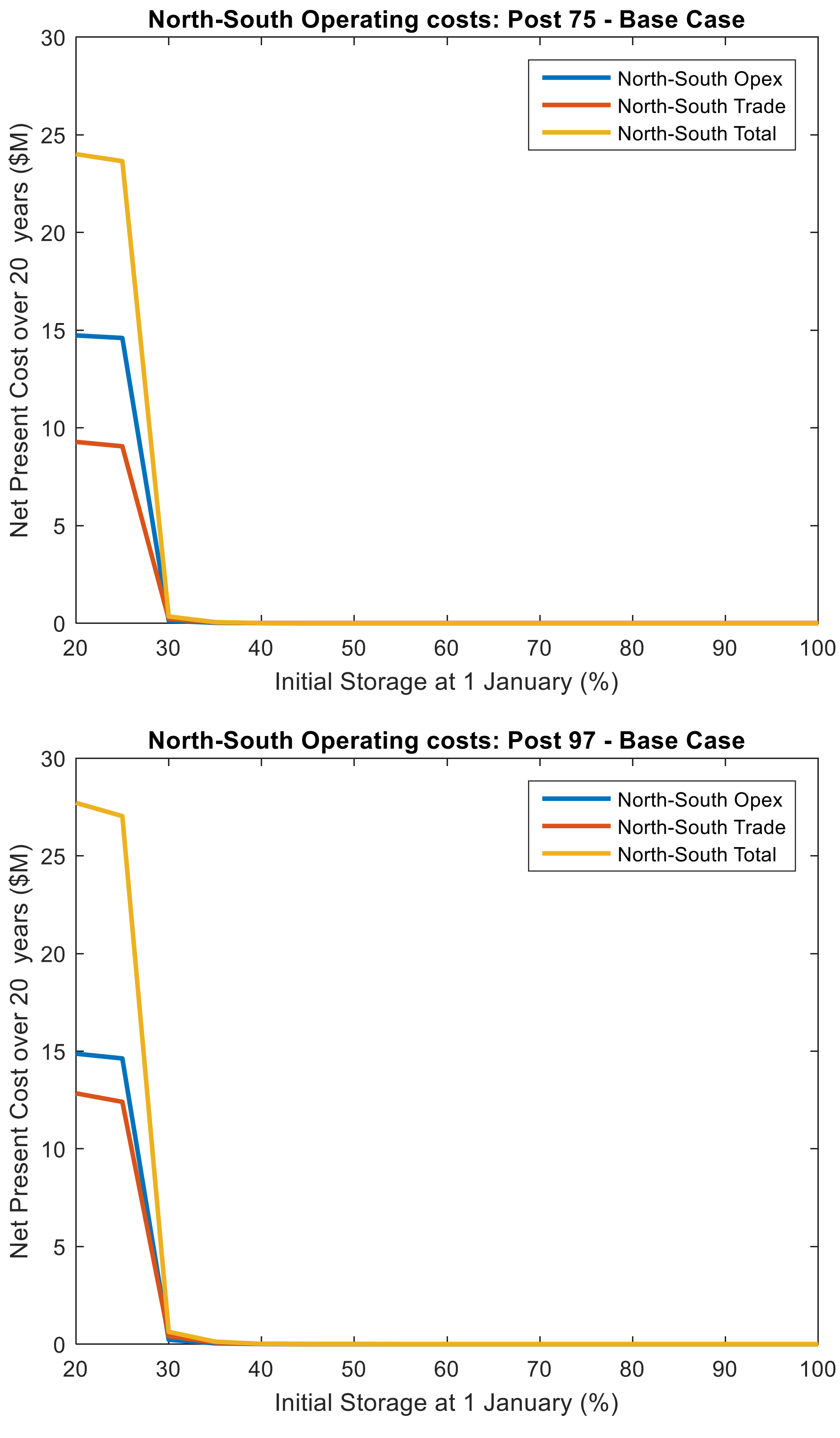


Figure 37: North-South Pipeline operating costs, Post 75 and Post 97 Base case.

Social costs associated with supply deficits

The social costs associated with supply deficits are hypothetical costs incurred if the water supply system is unable to supply Stage 4 restricted demand. These are assumed to be extremely expensive outcomes and only occur in just over 300 of the simulations in the Post 75 realisations, for $S_0 \leq 30$ per cent. They are more frequent in the Post 97 realisations and occur for $S_0 \leq 40$ per cent. Shortfall events occur for around 3% and 7.5% or realisations, for the Post 75 and the Post 97 cases respectively, for

S_0 = 20 per cent. This is a high rate of supply failure in the modelled realisations, but this residual risk can be significantly reduced by acting to augment before storage reaches such critically low levels.

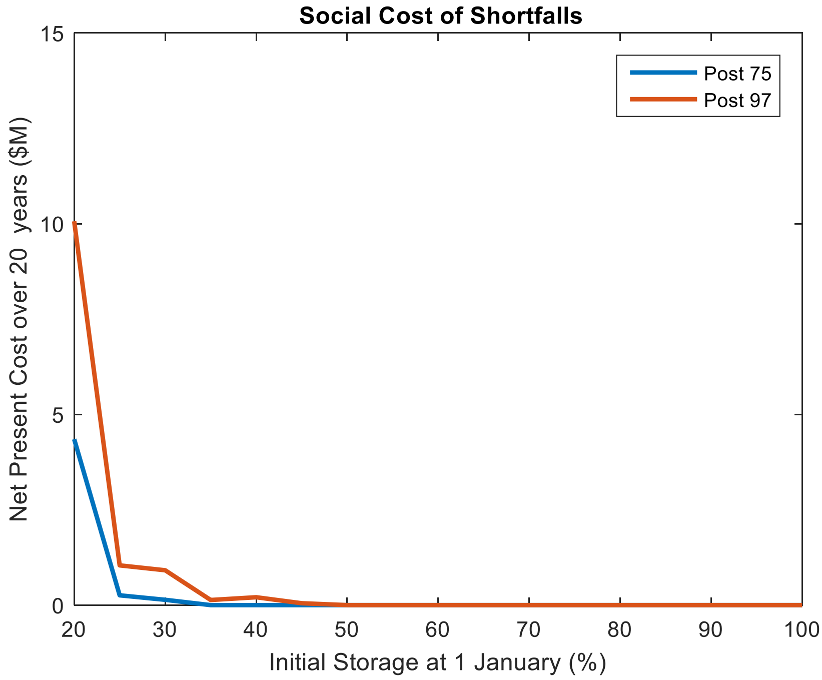


Figure 38: Social costs associated with deficits, Post 75 and Post 97 Base case.

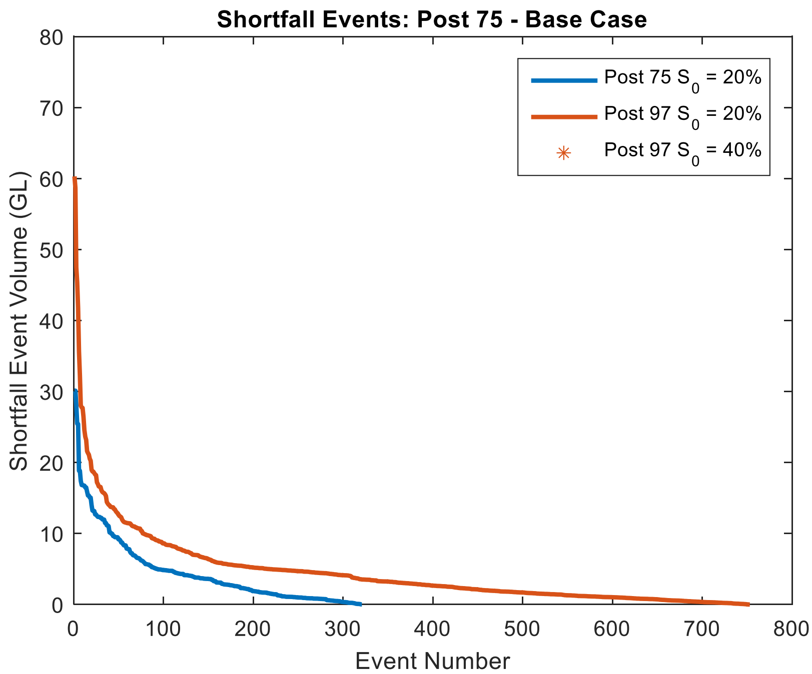


Figure 39: Frequency of supply deficits, Post 75 and Post 97 Base case.

Reliability Cost Curve: Base Scenario

Combining the individual expected costs from the modelled scenarios associated with maintaining a reliable water supply over the twenty years provides the reliability cost curve (Figure 40). The RCC for the Post 75 set of hydrological realisations shows the costs associated with meeting the target demand for water over twenty years. This figure shows that the expected costs range from almost $100 million to almost $1,500 million in net present value terms over that twenty-year timeframe. For initial storages between 100 per cent and 70 per cent full the RCC is almost entirely based on future augmentations of the water supply system. That is because in 55 per cent of the simulations the augmentation of the VDP is triggered and the RCC represents the time and probability discounted costs of those augmentations.

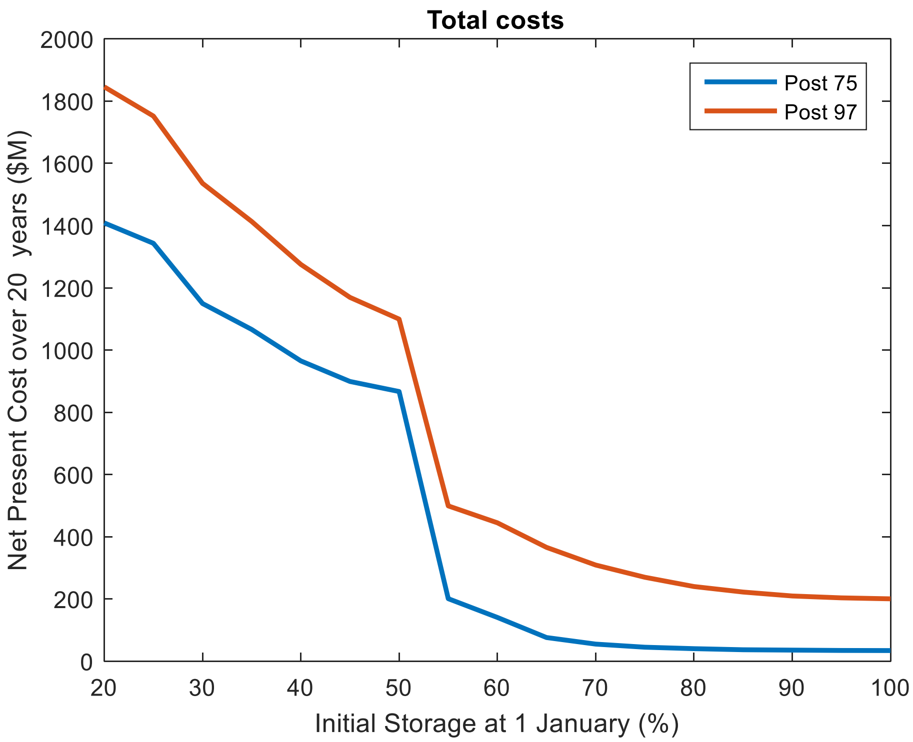


Figure 40: Total costs of supplying water, Post 75 and Post 97, Base case.

The modelling highlights that as the initial storages fall from 70 per cent, the augmentation of the VDP is increasingly likely until it is always triggered below 55 per cent storage. From 65 per cent to 30 per cent initial storages, there are a number of costs that contribute to the RCC, starting with operating the desalination plant and imposing restrictions. At 40 per cent initial storages, not only is the expansion of the VDP triggered, but in 13 per cent of the simulations an additional desalination plant is also required. When initial storages are at 20 per cent, then the assumed additional desalination plant is commissioned 22.5 per cent of the time in the Post 75 hydrological realisations.

The RCC for Post 97 case is considerably higher at every initial storage level than with the Post 75 hydrological realisations, ranging from over $200 million when storages are initially completely full to approximately $2,000 million when they are initially 20 per cent full. This is because Melbourne's water supply system is not sufficiently reliable with demand growth and the inflow realisations over the next 20 years under the Post 97 hydrological realisations to meet expected demand and in many of the realisations and it requires additional augmentations regardless of initial storages. When initial storages are at 100 per cent the VDP is expanded in half the realisations (Figure 4).

As the initial storages fall, the probability of requiring an augmentation of the system increases until it reaches the augmentation trigger at just over 50 per cent. The difference is that the probability of additional augmentations of the water supply system increase until, when storages are at 40 per cent initially, the hypothetical additional desalination plant used in this study is built in 25 per cent of the simulations.

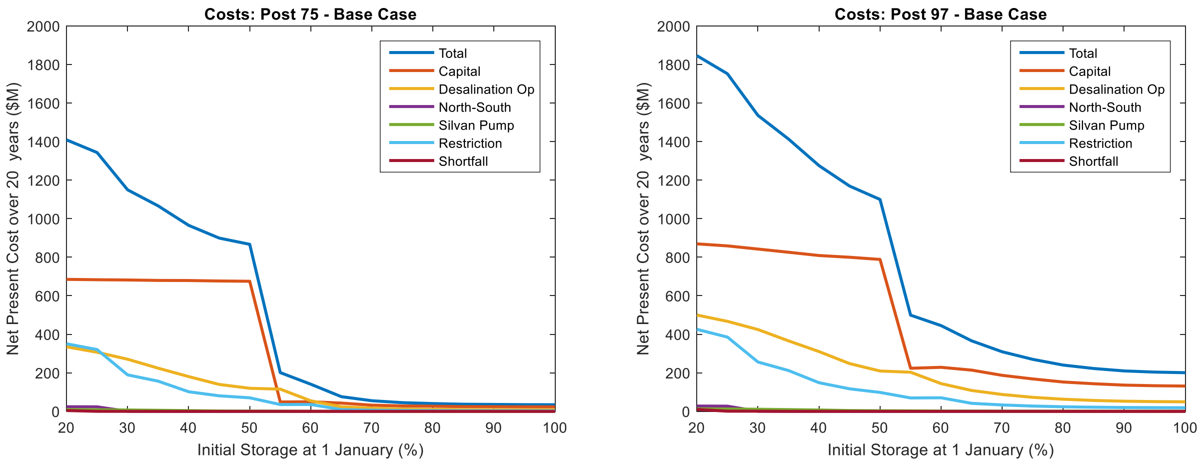


Figure 41: Components of the RCC, Post 75 and Post 97 Base case.

The RCC, and the marginal value of the RCC, provide important information on a number of key decisions that water supply system managers are typically required to consider. These include the decisions on:

1. What price to trade water at, based on the marginal value of the RCC and the initial storage level;
2. How to operate the water supply system to lower the expected RCC; and
3. Planning for major augmentations to the water supply system over the long term.

The marginal value of the RCC, the economic value of water in storage, can be used to determine what price to trade water. This is discussed in the next chapter. In addition, the next chapter explores how consideration of alternative operational arrangements or planning decisions influence the RCC, providing important information about how to reduce the long-term costs of supplying water reliably. These alternative RCC expected costs can be used to support information to optimise, over the long term, the way in which the water supply system is managed and the way in which future potential augmentations are planned, evaluated and incorporated within existing decision making processes.

Chapter 5: The economic value of water in storage

The RCC shows the long term expected cost associated with delivering water for a given set of hydrological realisations. Examining how the RCC changes as the initial amount of water in storage changes provides an assessment of the economic value of water in storage. The Victorian Water plan states:

> "The enhanced connectivity of the grid allows areas outside Melbourne to benefit from the increased water security provided by the desalination plant. We have an opportunity to share the benefits of this water security and to build drought resilience. All benefits, costs and risks need to be recognised and assessed." (Victorian Government, 2016).

Knowing the marginal value of water in storage enhances the ability to realise the benefits associated with the water grid and markets that are being created in Victoria. An accurate estimate of trading water into or out of the Melbourne water supply system needs to incorporate how the cost of maintaining a reliable supply changes based on the quantity moving in or out.

The economic value of water in storage, expressed as the marginal reliability cost, is shown in Figure 42. It is worth noting that the shape of the marginal total cost curve is very similar between the two sets of hydrological realisations, notwithstanding the slightly higher marginal NPV for the Post 97 base case, which has an average streamflow about 25% less than the Post 75 case (Table 9). As a consequence, the storage at which the marginal reliability cost crosses key supply costs, such as operating the desalination plant, is relatively insensitive. Another key difference is that the marginal NPV for the Post 97 base case starts at a higher initial storage level than in the Post 75 base case and ends at a higher point. The reason for the differences between Post 75 and Post 97 relates to the difference in stream flows and hence the probability that an augmentation (and other actions including operating the desalination plant) might be triggered.

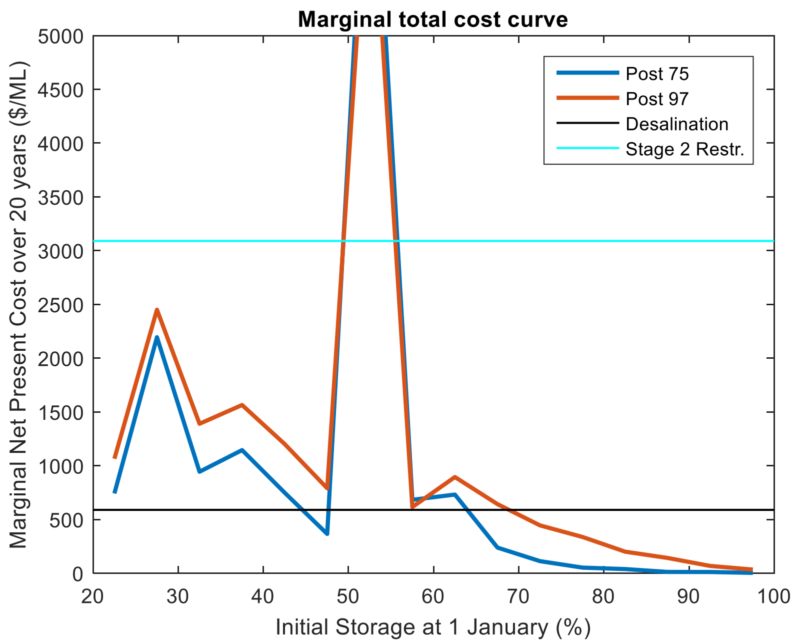


Figure 42: Marginal Reliability Cost, Post 75 and Post 97 Base case, Marginal Costs of Desalination and Stage 2 Restrictions.

The decision to move water in or out the Melbourne water supply system should be made with consideration as to how it influences the long-term costs associated with maintaining a supply of water. For instance, as Figure 43 shows, the value of water to the Melbourne water supply system varies considerably depending on current storage. When storages range between 60 and 65 per cent, a megalitre of water is worth almost $1,000 in the Post 97 base case. This is because additional water in storages at that point helps avoid potentially expensive augmentations of the water supply system. When initial storages are between 75 and 80 per cent, the marginal value of water is almost $400 per megalitre.

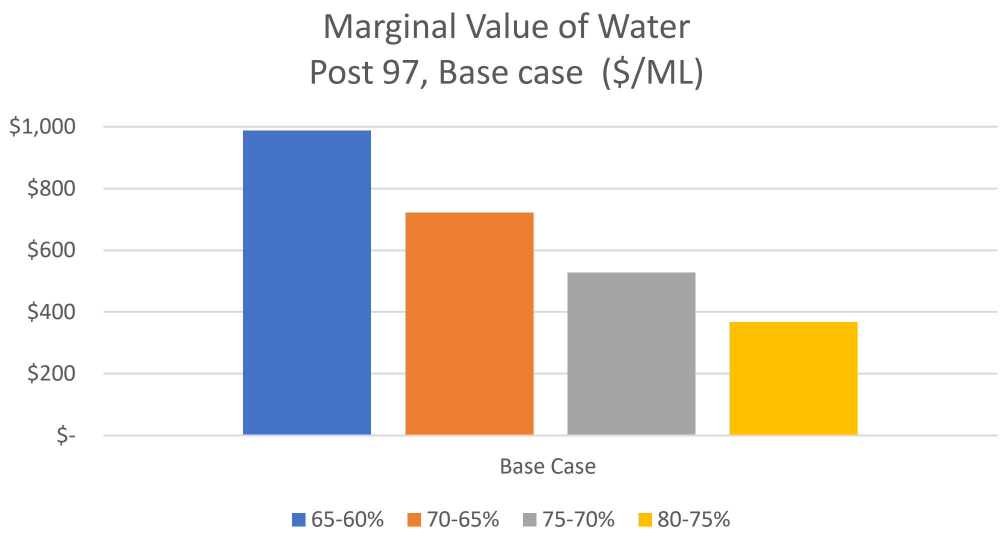


Figure 43: Value of water in storage, Post 97 Base case, select initial storages

The water grid that has been established in Victoria has the opportunity to enhance the level of water security and provide water authorities with more options to mitigate risk. However, the economic value of water in storage has been calculated on the basis of meeting forecast demand in Melbourne. Geelong has already taken water from the Melbourne system and, subject to trades between water corporations, can just as easily be supplied with desalinated water in the future. The rapidly growing populations of Sunbury and Melton, already connected to the Melbourne system, can also be supplied with desalinated water.

This study does not consider the costs and benefit associated with transferring water from other entitlement holders to provide water to the Melbourne area. The study does not consider constraints, technical or otherwise, that might require consideration in the implementation of the scenarios addressed in this study.

Chapter 6: Scenarios – operating the system efficiently

The RCC for the base case operating arrangements represent the expected costs as a function of initial storage associated with supplying water demand scenarios to Melbourne over a 20 year horizon under two different hydrological realisations. Examining how the RCC changes as operating arrangements change allows the economic efficiency of various water management decisions to be evaluated. These include potential to inform decisions on:

1. How to operate the water supply system to lower the RCC; and
2. How to plan for major augmentations to the water supply system.

The scenarios to be examined include:

1. Changing the trigger storage level adopted for this study for operating the desalination plant, with an initial storage level of either S_t< 0.55, for low desalination; or
2. S_t< 0.75for high desalination;
3. Altering when water might be accessed through the North-South Pipeline; or
4. Reducing the lead times for augmenting the system which, for this study, is assumed to be through the construction of desalination plants.

Examining the total costs under the alternative scenarios reveals that there are alternative operating arrangements that might significantly reduce the total expected costs of maintaining a reliable water supply over the twenty-year planning period.

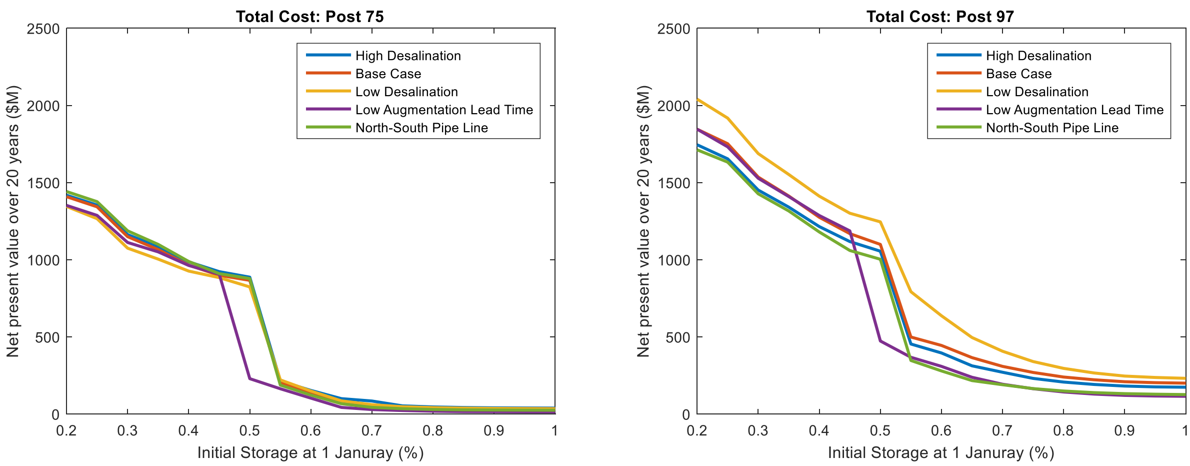


Figure 44: RCC, Post 75 and Post 97, alternative scenarios.

For the post 75 hydrological realisations, having a short augmentation lead time reduces the total costs associated with supplying water for almost all ranges of the water supply system storage, but particularly around 50 per cent initial storage. The reason is that the post 75 hydrological realisations have a high degree of reliability. It is only as water storages approach fall below 50 per cent, in the low lead time scenarios, that the augmentation is triggered. This reduces the RCC for all storages above an initial storage of 50 per cent. Based on the Post 75 hydrological realisations, and an initial storage level of 60 per cent, the long-term costs associated with meeting Melbourne's expected water demand could be reduced by approximately $30 million if the augmentation lead time could be reduced. For the study, at the 60 per cent initial storage level, variation through a higher trigger storage for the North-South Pipeline may reduce the expected costs by $10 million.

In the post 75 hydrological realisations, the modelled operating rule for the desalination plant does not have a substantial influence on the expected costs. This is because the system is highly reliable under this set of expectations and, as a consequence, the desalination plant's operation does not significantly influence the need or probability of augmentation. This highlights the RCC to the hydrological realisations adopted and, in the case of lower streamflows in the Post 97 realisations, the augmentation options available.

Under the post 97 hydrological realisations there is more capacity to reduce the overall cost of delivering water as decisions have a greater influence on the probability and timing of future augmentations. Based on initial storages of 60 per cent, there is scope to reduce the costs of maintaining a reliable water supply by between approximately $110 million to almost $130 million over the planning period. The modelled scenarios that produce lower expected costs are associated with a shorter augmentation lead time and with possible variations in the utilisation of the North-South Pipeline. Neither of these options is optimal over the entirety of the initial storage levels of the water supply system. Unlike the post 75 realisations, in the post 97 realisations the operating rule of the desalination plant makes a significant difference to the RCC. For instance, turning the desalination plant on at a lower storage level (1 December storage of 55% compared with 65%) would increase the RCC by almost $150 million at an initial storage of 60 per cent.

The most important difference in costs between the different scenarios is variation in the augmentation capital costs (Figure 45). The reason that the total costs of alternative scenarios differ relates to how frequently the costs of various actions associated with maintaining a reliable water supply are incurred. By operating the desalination more frequently, at a higher storage, a greater buffer for drought conditions is created in the water supply system in the Post 97 realisations. As a consequence, the percentage of realisations requiring an augmentation is halved at storages above 55 per cent when operating the desalination plant more frequently. Not operating the desalination plant frequently results in more augmentations at higher levels of initial storage in the Post 97 realisations.

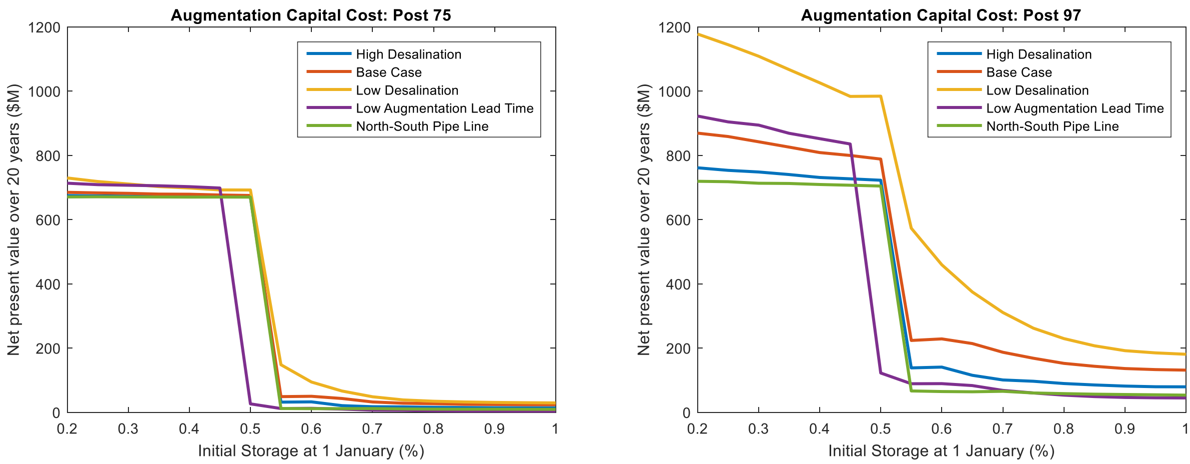
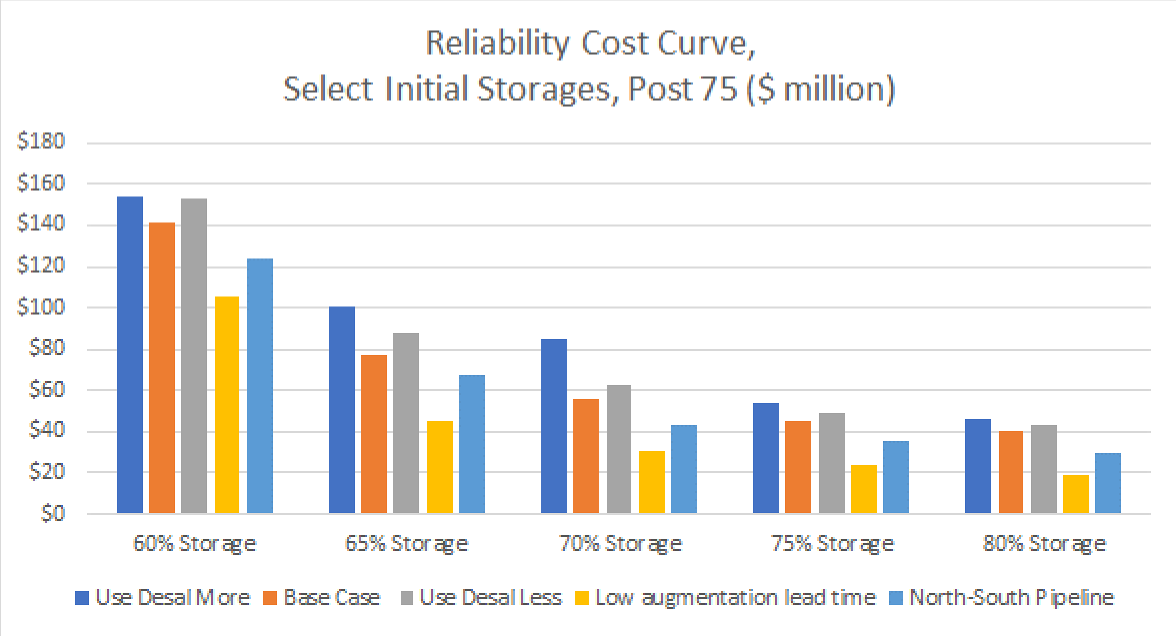


Figure 45: RCC, Post 75 and Post 97, alternative scenarios.

It should be noted that reducing the length of time required to augment the water supply system results lower costs for maintaining reliability. This is because it results in fewer emergency augmentations at every level of storage as storages can be allowed to fall further if an augmentation can be brought on line more quickly.

The situation is different under the Post 75 realisations. In these simulations the water supply system is highly reliable, not requiring an expansion of the VDP often unless the initial storages are below the trigger level for the augmentation. However, it should be noted that the lower augmentation timeframe reduces the storage level where the expansion of the water supply system occurs and would produce cost savings.

The timing of different elements of maintaining a reliable supply of water, the differences between the alternative RCCs at select initial storages is illustrated in Figure 46. These charts highlight the different NPV costs of maintaining a reliable supply associated with each scenario at a specific level of storage.



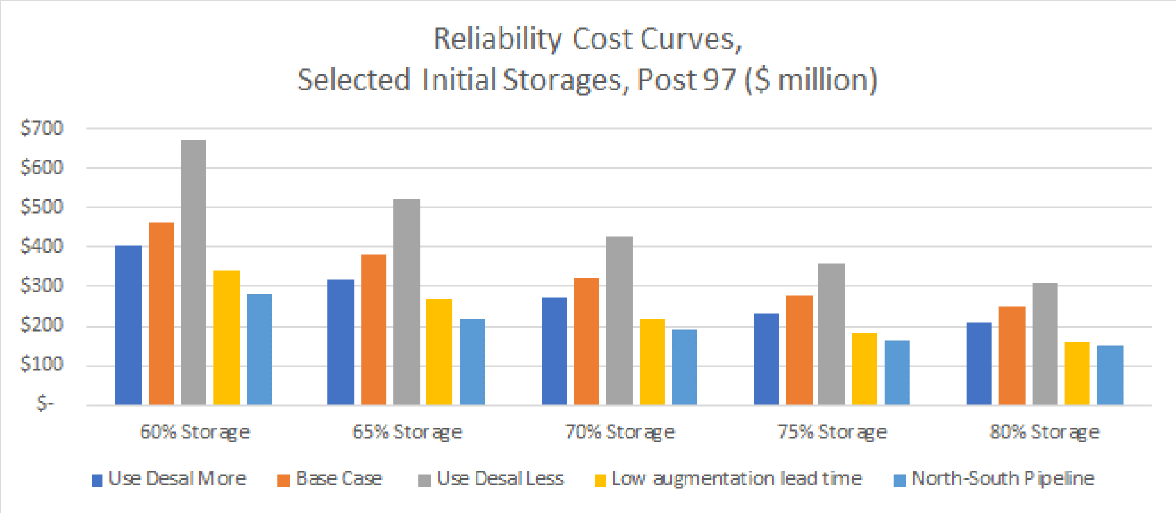


Figure 46: Reliability cost curves for alternative scenarios, Post 75 and 97, selected initial levels of storage.

In the Post 75 realisations, at 70 per cent initial storage, reducing the timing of the hypothetical VDP expansion reduces the expected costs of supplying water, compared to the base case, by $25 million, or 45 per cent of the anticipated costs. This is because having a shorter augmentation timeframe means that the water supply system expansion is potentially triggered less frequently. Given that the water supply system is highly reliable in the Post 75 realisations, avoiding augmentations creates considerable value.

In the Post 97 realisations, at 70 per cent initial storage, reducing the timing of the hypothetical VDP expansion reduces the expected costs of supplying water by $104 million, or 32 per cent of the anticipated costs, compared to the base case. This is a significant reduction in the anticipated costs associated with supplying water and suggests that there are considerable benefits associated with planning and preparing for the expansion of the water supply system. In addition, consideration of the potential option to use the North-South Pipeline more frequently results in $129.7 million of savings, or 40.3 per cent of the anticipated costs. Utilising the desalination plant more frequently could result in savings of $47.5 million, or 14.7 per cent of anticipated costs at 70 per cent initial storages compared to the base case.

At lower levels of storage the differences in scenarios is even more significant. Consider the Post 97 realisations. At 60 per cent initial storages, the scenarios examined suggest that the long-run costs of meeting expected demand could be reduced by $59 million, or 12.8 per cent of the long-term costs, compared to the base case by operating the VDP at higher initial storages. Alternatively, by undertaking pre-planning for future augmentations, or considering the potential option to use the North-South Pipeline more frequently, the cost of maintaining a reliable water supply could be reduced by $119 million or $180 million, between 25 to 39 per cent, compared to the base case. The benefits of alternative scenarios vary based on the initial storage. However, operating the VDP at higher initial storages reduces the expected costs at all levels of storage.

The scenarios examined suggest that the cost of delivering water to Melbourne could be further optimised and reduced by incorporating the cost of maintaining reliability into modelling and management decisions.

Chapter 7: Long and short-run marginal costs & the RCC

The RCC provides very different information about the value of additional water in the water supply system than estimates of the Long-Run Marginal Cost of supplying water. The Long-Run Marginal Cost is calculated based on long term estimates of the available resource and expected demand and tend to be neutral to the current level of water in storage.

Long run marginal cost measures

The two most commonly used measures (Howe, 2005) of long term marginal costs are the Perturbation or Turvey approach (Turvey, 1976) and the average incremental cost (Saunders, 1976). Turvey (1976) defined the marginal capital cost of water supply as the cost savings from postponing a capacity addition scheme. It is calculated by forecasting demand under current policies over the medium to long term while considering the capacity of existing water supplies to supply unconstrained demand over that period. The least cost program of capital works that enables water supply with unconstrained water demand is then estimated. The next step is to marginally change demand, either up or down, and estimate the capital works program required. The Turvey long run marginal cost is then the present value of the difference between the original and revised capital works program divided by the value of the change in demand required to achieve it (Equation 8).

$$\text{Turvey LRMC} = \frac{PV(revised\ investment\ expenses - optimal\ investment\ expenses)}{PV(revised\ demand - unconstrained\ demand)} \qquad 8$$

where investment expenses include capital and operating expenses. It should be noted that the Turvey method was developed to provide the long run marginal cost of operation and treatment plants, which are significant sources of expense for water utilities and the dominate expense in the UK where it was developed, and *not* for investments in storage capacity.

The average incremental cost method (defined by Saunders and Warford, 1976) calculates the long run marginal supply on the basis of the next best available supply augmentations over a period in time. This involves forming an expectation of long term hydrological inflows, forecasting the present value of unconstrained demand over the same time, and identifying a capital works program to meet capacity requirements over that period. The LRMC in this approach includes an allowance for both the cost of the capital to construct the plant and also its operating costs (Equation 9):

$$\text{AIC LRMC} = \frac{PV(water\ supply\ capacity\ expansion)}{PV(additional\ demand\ serviced)} \qquad 9$$

A price based on the long run incremental cost provides investment signals to present and potential future water consumers at the expense of short run efficiency. It includes the short run marginal costs of providing water plus an annualised charge reflecting the costs associated with the next investment required. Potentially overcharging for short term use. Under this approach, price changes occur immediately after an investment to reflect the cost of the next investment.

Water industry regulators often prefer pricing with reference to LRMC since the water and wastewater sectors are generally highly capital intensive and characterised by 'lumpy' investment in new capacity (NERA, 2012 #101). At any one time, most water and/or wastewater systems operate with some spare capacity such that the system is capable of serving additional demand at relatively low or zero cost. Given this, marginal costs are generally measured on the basis of the change in the per unit costs of supply associated with permanent step changes in forecast demand that require some level of additional capital investment. The theoretical relationship between the short run and long run marginal costs are described in Figure 47.

In this chart the blue line represents a LR MC estimate while the red line reflects the SR MC that is changing as short-term storage changes. Economic theory suggests that when shortages of supply develop the short run marginal cost of supply will rise to ration water use, as will the long run marginal cost. However, when water supply systems have reserve capacity, it can be difficult to define the hydrological expectations that constitute "available resource" to be rationed.

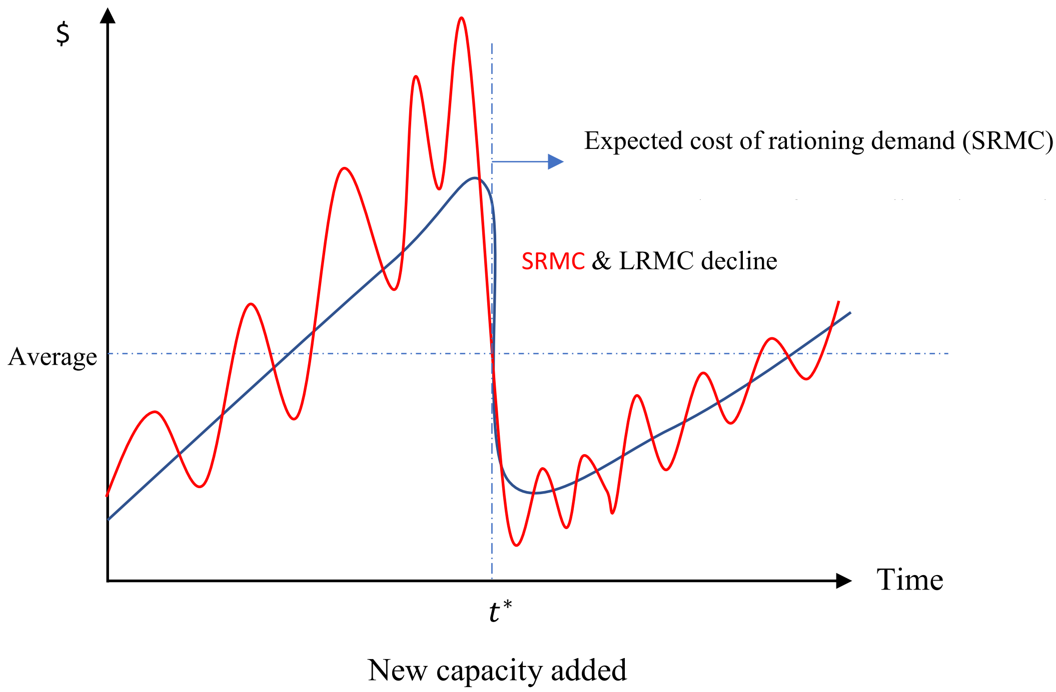


Figure 47: Short and long term marginal costs.

Just as hydrologists tend to treat demand as a fixed quantity, so economists tend to simplify hydrological uncertainty. The "capacity constraints" that scarcity prices attempt to measure only exist in terms of long-term hydrological expectations. A key challenge to determining long term expectations is the variability of hydrological systems that exhibit cyclical behaviour that can stretch from sub-annual to multi-decade (Hurst, 1951 #83). For instance, in south-east Australia rainfall is influenced by uncertain climate patterns that can range from five to seven years, in the case of the El Nino influence, and 20 or 30 years in the case of the multi-decadal Pacific Oscillation (Kiem, 2004 #82).

In addition to the stochasticity of hydrological inflows, it is difficult to define periods of shortfall. Drought is a "creeping phenomenon" (Gillette, 1950 #84), making an accurate prediction of either its onset or end a difficult and contested task. Current measures of short run marginal cost do not "ration the resource" as there are considerable uncertainties about the resource that requires rationing. According to (Tannehill, 1971 #85), "The first rainless day in a spell of fine weather contributes as much to the drought as the last, but no one knows how serious it will be until the last dry day is gone and the rains have come again …. we are not sure about it until the crops have withered and died."

The consequence is that hydrologists underestimate the variability and responsiveness of demand to pricing, and economists fail to appreciate the degree to which variation in hydrological outcomes can influence the performance of reservoirs. Given the stochasticity of hydrological inflows, it may be that a correct estimate of hydrological uncertainty has been made, and appropriate levels of infrastructure attributed to it. However, in the short term, the population may die of thirst waiting for future floods to replenish reservoirs. As John Maynard Keynes said, "In the long run everyone is dead."

With climatic variability, even highly reliable reservoirs, with significant “excess” storage capacity, can require augmentations during periods of prolonged low inflow. The Melbourne Water System Strategy sets out three strategic scenarios of supply and demand and outlines when the water supply system requires augmentation. These scenarios are:

1. low change scenario: lower growth in water demands and low climate change and no water shortages anticipated by 2065;
2. incremental change scenario: medium growth in water demands and medium climate change with potential water shortages of 100 GL per year emerging by 2065, with water shortfalls beginning to emerge by 2043; and
3. rapid change scenario: higher growth in water demands and high climate change. In this scenario the shortfall of water is 450 GL per year by 2065 with water shortfalls emerging by 2028.

Consider how the timing of augmentations vary based on the initial storages for the two base cases presented in this report (Figure 48 and Figure 49). Examining when augmentations take place based on the initial storages suggests that (Grafton, 2014 #6) was correct in observing that there is no optimal investment as it depends on current conditions. When storages are completely full, and Post 75 hydrological realisations are considered, the most reliable expected inflows, Melbourne’s water supply system is augmented in 10 per cent of the inflow realisations within 20 years. The importance of incorporating the need for augmentations in current operating decisions is highlighted by the fact that if storages are allowed to fall to 40 per cent, then in 2 per cent of realisations, a second desalination plant needs to be built to maintain reliability, whereas this is avoided if storages are maintained above 60 per cent. At 40 per cent initial storage, further augmentations of the water supply system would be needed in 25 per cent of the realisations.

Under the Post 97 hydrological realisations, the influence of the initial storage level is even more important. This is highlighted by the fact that at 100 per cent initial storage realisations, the water supply system will be augmented by the 50,000 ML expansion of the VDP in almost half the simulations and further augmentations, assumed for this study to be a second desalination plant, are also built in 3 per cent of simulations. In contrast, when the initial storage is 60 per cent, 57.5 per cent of the simulations require the VDP to be expanded while 7 per cent require a second desalination plant, as assumed in this study, to be constructed.

The advantage of the RCC is that it makes the economic impact of variations in water storage explicit and enables this to inform different operating arrangements. It is important to include the RCC, and the costs associating maintaining a reliable water supply over the planning period, in trading, operation and augmentation decisions to reduce the long term expected costs associated with meeting demand.

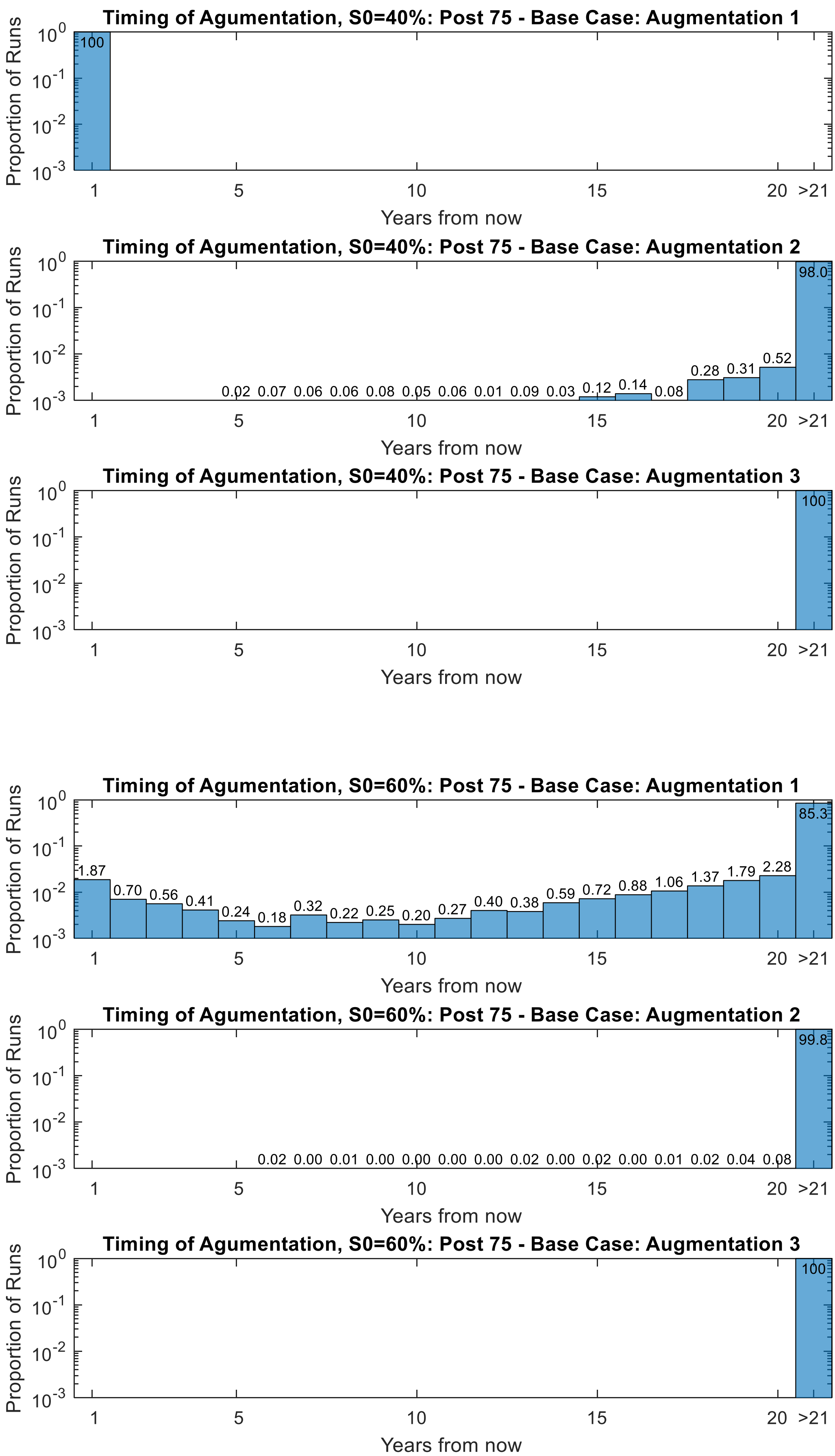


Figure 48: Augmentations timing, Post 75 Base case.

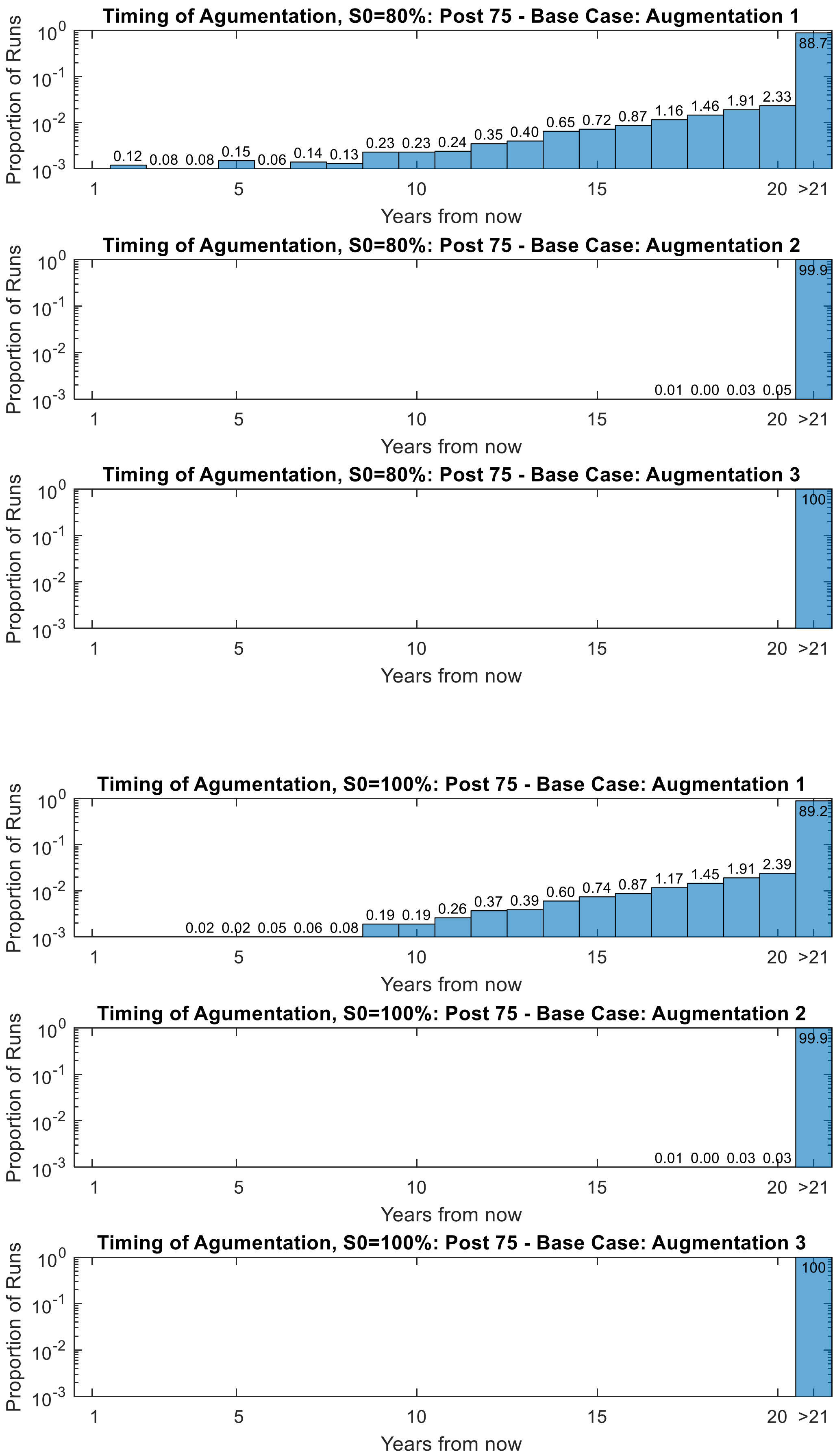


Figure 48 continued: Augmentations timing, Post 75 Base case.

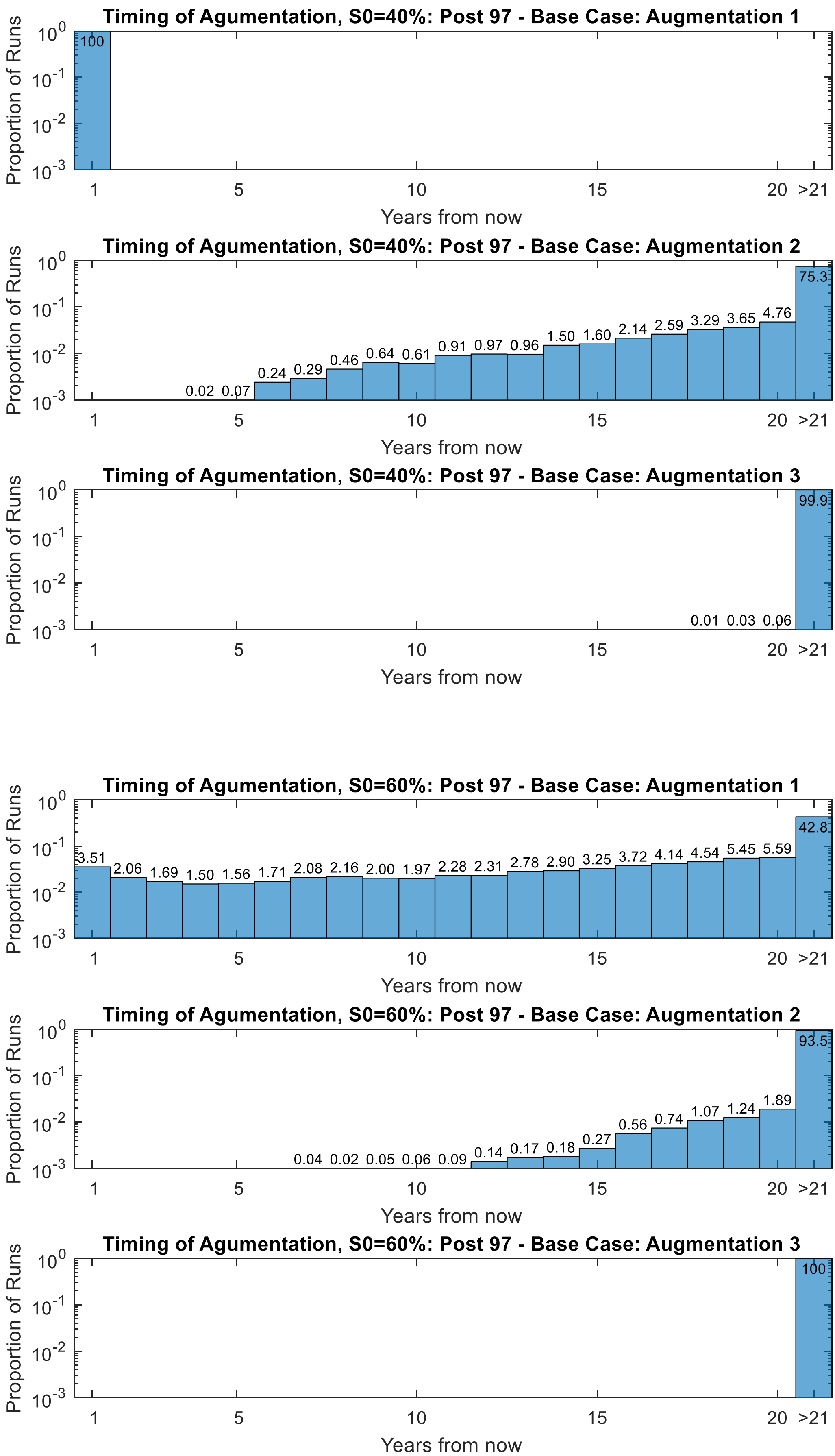
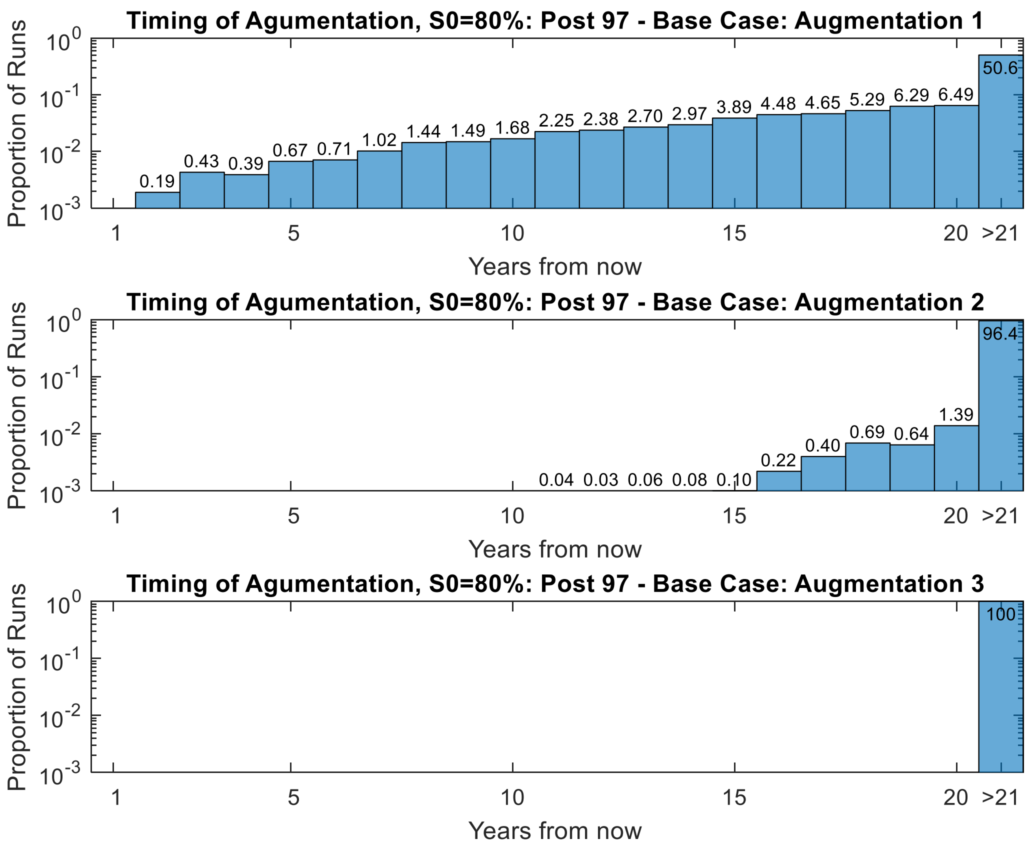
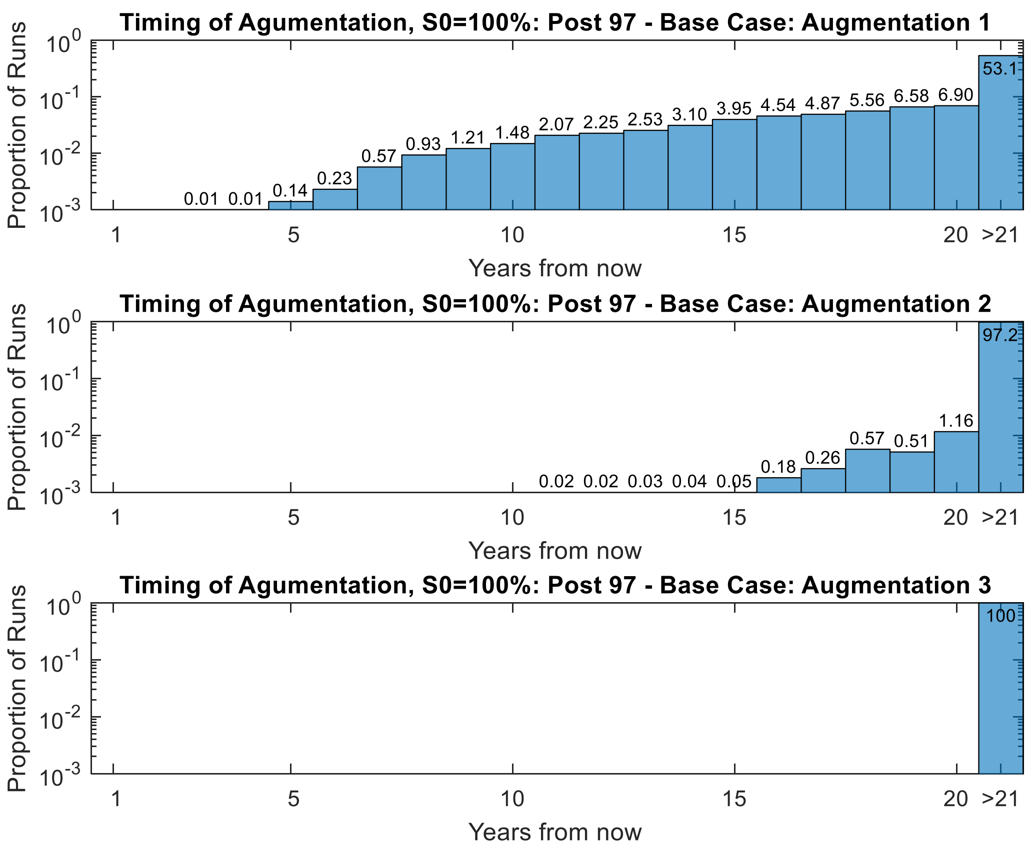


Figure 49: Augmentations timing, Post 97 Base case.


Timing of Agumentation, S0=80%: Post 97 - Base Case: Augmentation 1
Proportion of Runs
Years from now
0.19 0.43 0.39 0.67 0.71 1.02 1.44 1.49 1.68 2.25 2.38 2.70 2.97 3.89 4.48 4.65 5.29 6.29 6.49 50.6
Timing of Agumentation, S0=80%: Post 97 - Base Case: Augmentation 2
Proportion of Runs
Years from now
0.04 0.03 0.06 0.08 0.10 0.22 0.40 0.69 0.64 1.39 96.4
Timing of Agumentation, S0=80%: Post 97 - Base Case: Augmentation 3
Proportion of Runs
Years from now
100


Timing of Agumentation, S0=100%: Post 97 - Base Case: Augmentation 1
Proportion of Runs
Years from now
0.01 0.01 0.14 0.23 0.57 0.93 1.21 1.48 2.07 2.25 2.53 3.10 3.95 4.54 4.87 5.56 6.58 6.90 53.1
Timing of Agumentation, S0=100%: Post 97 - Base Case: Augmentation 2
Proportion of Runs
Years from now
0.02 0.02 0.03 0.04 0.05 0.18 0.26 0.57 0.51 1.16 97.2
Timing of Agumentation, S0=100%: Post 97 - Base Case: Augmentation 3
Proportion of Runs
Years from now
100

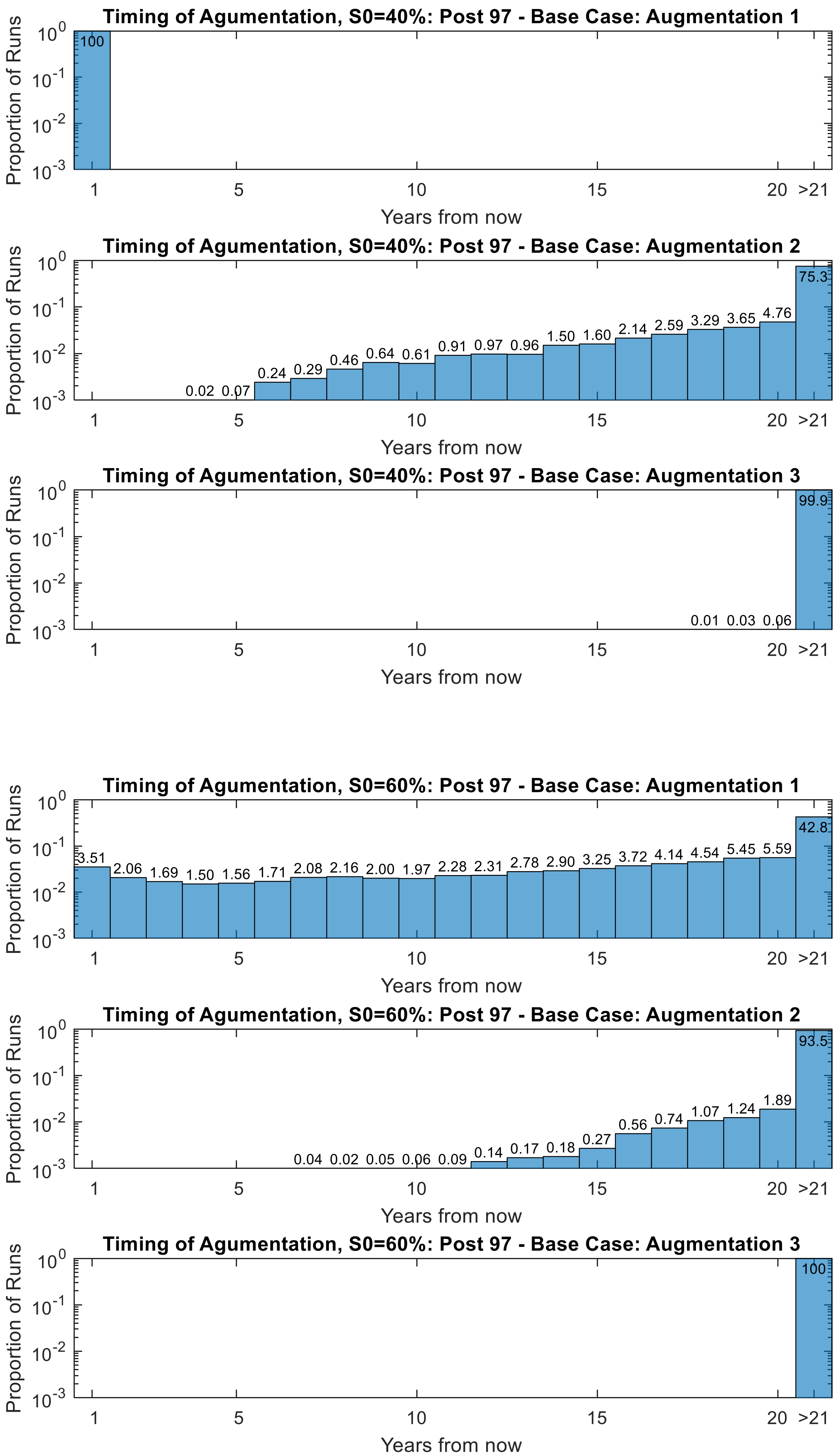


Figure 49 continued: Augmentations timing, Post 97 Base case.

Appendix 1: The social cost of restrictions literature review

It is sometimes argued that having a fixed target demand is justified if demand is not highly responsive to price (Howe and Linaweaver, 1967). If demand is inelastic, then price will be an ineffectual tool for rationing supply and that other mechanisms are more appropriate, such as water use restrictions, public education campaigns, and demand management programs intending to substitute more water efficient technologies. In addition, it allows for operation decisions to treat demand as endogenous. However, if demand for water is responsive to price, then the afore mentioned policies decrease consumer welfare, and result in social welfare losses.

In this report, the economic value of water in storage has been established based on a fixed, or expected, demand. This does not represent an optimisation of the water supply system. A second step would be to optimise the water supply system based on the responsiveness of demand to changes in price reflecting the scarcity of water. Below is a brief review discussion of the literature discussing the responsiveness of water demand to price.

The benefit of restrictions is that they provide a means of reducing water demand and, thereby averting catastrophic reservoir failure or, hopefully, pre-emptive or unnecessary augmentations. However, rationing a good to consumers who have heterogeneous preferences and different marginal valuations for the good is not economically efficient (Grafton et al. 2008). It creates social costs for consumers by distorting consumption behaviour and through supressing individual preferences. Mandatory water restrictions can also be costly to enforce, time consuming, and require a significant investment in education and marketing (White et al, 2002) and encourage vigilante behaviour (Cooper, Rose and Crase, 2012).

Water demand has been formally investigated by economists for half a century. This research has addressed a number of critical questions and issues that need to be addressed to quantify the economic value of water in storage. These are:

- Is demand responsive to price and how much?
- What are the social welfare costs associated with restrictions regimes?
- What is the relevant price to use?
- The data limitations of existing research; and
- The functional form of demand.

There is an extensive academic literature examining water demand, particularly price elasticity and also, to a lesser extent, income elasticities. Hanemann (1997) reviewed the theory and application of residential water demand analysis and identifies more than 50 articles and reports from the pre-1992 literature in the United States alone on the topic. Subsequent meta-analyses by Espey et al (1997) reviewed 24 journal articles published between 1967 and 1993 while Dalhuisen et al. (2003) examines a total of 64 studies over the same period. According to a survey of residential demand modelling by Worthington and Hoffman (2008):

> "Almost without exception, the estimated price elasticities are negative and inelastic (less than one), signifying the percentage reduction in the quantity of residential water demanded is less than proportionate to the percentage increase in price."

This suggests that demand will be influenced by construction of a pre-emptive or unnecessary augmentation.

Econometric techniques to estimate residential demand were first applied by Howe and Linaweaver (1967) and they found that demand was responsive to the price charged. They analysed data from US suppliers between 1963–1965, differentiated by region and according to indoor and outdoor uses. This is a similar to Danielson (1979) in examining indoor and outdoor use as it recognises that residential water use comprises two key elements: within-home use (showers and bathing, drinking, flushing the toilet, washing dishes and other cleaning uses) which is frequently considered the amount necessary to sustain life, and outside of the home uses (watering lawns, washing automobiles watering gardens and trees, washings sidewalks and driveways pools) which is often recognised as more discretionary. However, it has become more common in subsequent analysis of the influence of price on demand (Hughes et al 2009, Grafton et al, 2015).

In Howe and Linaweaver (1967) the water price used for their study combined the value of the marginal water and sewage price blocks in which the average consumption was observed. They argued that consumers react to marginal rather than average prices (as did Danielson 1979; Lyman 1992). Quantity was the average water use per account per day. They found that price elasticity was greater for outdoor uses than indoor. In 1982, Howe re-estimated marginal price elasticities with the same data, utilizing more appropriate forms of household water demand functions derived from advances in consumer theory that account for the effects of a rate structure. Winter season elasticity was found to be a very low −0.06 compared to −0.23 in the 1967 study. For summer demands, price elasticities are found to be lower than earlier estimates, namely, −0.568 versus −0.860 for eastern US areas and −0.427 versus −0.519 for western areas.

Espey et al. (1997) conducted a meta-analysis of 24 journal articles published between 1967 and 1993. Their analysis contained 124 estimated price elasticities with a wide range of demand specifications that included, indoor, outdoor, income, population density, household size, seasonality, rainfall and other factors. This clearly creates a more complex picture than the volumetric quantity based demand analysis underpinning hedging and operation arrangements put forward by Draper and Lund (2004).

Dalhuisen et al. (2003) conducted a more extensive meta-analysis that included 296 elasticity estimates from 64 journals published between 1963 and 2001. They found that the variation in estimated elasticities is associated with differences in the underlying tariff system. Relatively high price elasticities and relatively low-income elasticities are found in studies concerned with demand under the increasing block rate pricing schedule. In addition, studies that did not use the marginal price, such as those using average or Shin prices, result in comparatively higher absolute values of price and income elasticity. Based on their analysis, they reported a sample median price elasticity of -0.35 and the median income elasticity was 0.24.

Almost without exception, estimated price elasticities are negative and inelastic (Worthington and Hoffman, 2008). While some estimates are low, such as Carver and Boland (1980) or Thomas and Syme (1988) with elasticities less than 0.25, more lie in the range between 0.25 and 0.75 (see Agthe and Billings, 1980, Chicoine et al (1986) and Gaudin et al. 2001). A potential cause of discrepancy is the price estimate is the time being measured. Arbues et al. (2003) suggests that long-run price responsiveness is likely to be higher as there is greater capacity for consumers to respond to the price change by investing in alternative technologies, such as water efficient showers or changing their gardens. This suggests that wealthier households have greater capacity to adjust, as Thomas and Syme (1988) and Renwick and Archibald (1998) found.

The findings for income elasticity almost always find that it is less than one, income inelastic, and small in magnitude (see, for instance, Chicoine et al. 1986, Moncur, 1987, and Garcia and Reynaud, 2003).

In Australia, Hoffman et al. (2006) conducted a panel study of urban water demand in Brisbane and estimated price elasticity to be between -0.67 and -0.55. Another panel study by Xayavong et al. (2008)

conducted in Perth estimated an indoor elasticity of between -0.70 and -0.94 while the outdoor elasticity ranged between -1.30 and -1.45. Barrett (1996, 2004) finds that the price elasticity of demand for residential water in Australia is typically around -0.5.

Estimates of social welfare losses associated with restrictions

In the United States, approximately 24.6 per cent of the country (excluding Alaska and Hawaii) was experiencing moderate to extreme drought conditions as of 2015, with drought conditions starting in 1997 in many areas (National Climatic Data Center, 2015). Residential consumers in the US have been estimated to value water reliability, measured by their willingness to pay to avoid restrictions, at USD $109 – 421 per household per year (Raucher, 2005). Analysing data from 1082 households in 11 urban areas in the United States and Canada, Mansur and Olmstead (2011) estimated that the welfare costs of restrictions were approximately $96 per household during the dry period which was approximately 29 per cent of average annual household expenditures on water in our sample. There was also high levels of heterogeneity in household preferences.

In Australia, Blamey, Gordon, and Chapman (1999) undertook a choice modelling survey of Canberra residents in the late 1990s. This survey sought to compare alternative supply and demand responses to water scarcity and found that, on average, respondents were prepared to pay $150 to reduce water demand by 20 per cent through the use of voluntary measures and incentives for recycling. Another study conducted in Canberra used choice modelling to focus on the marginal willingness to pay to avoid water restrictions (Hensher, Shore, and Train, 2006). This survey, conducted in 2002-03, found that residents were willing to pay an average amount of $109, $130 and $268 per year to avoid water restrictions at level 3, 4, or 5 respectively.

Grafton and Ward (2008) estimated that the social cost associated with water restrictions in Sydney was $55 per person in 2005 or approximately half the water bill. They did so by estimating how much people have paid to substitute for water restrictions, via water tanks or other arrangements, and estimating the cost for Sydney as a whole. Bryon et al. (2008) extrapolated these costs to the 80 per cent of households subject to water restrictions and found a national social cost of around $900 million per annum due to water restrictions.

The Productivity Commission (2010) estimated that the social costs of water restrictions were approximately $100 million per year relative to introducing scarcity pricing. This was equivalent to approximately $110 per household annually, or more than 15 per cent of the average household's $658 water bill (NWC, 2009).

Cooper et al. (2012) undertook a contingent valuation study to examine the welfare gains associated with household's willingness to avoid water restrictions. They found that the willingness to pay was significantly influenced by the characteristics of the household with, for instance, respondents with lawns willing to pay $157 to avoid restrictions compared to $113 for those without. Furthermore, relatively wealth respondents were willing to pay between $182 and $292 to avoid restrictions compared to less well-off respondents who were willing to pay between $119 and $229 to avoid restrictions.

As Cooper et al. (2012) state: "restrictions are not just a means of demand management but valued as part of a sense of community building and a sense of shared hardship." Aisbett and Steinhauser (2014) examined water usage data for the ACT from 2005 through to 2010 to model voluntary responses to water shortages and found that a 10 per cent decline in storage levels would induce voluntary conservation reductions of 4.5 per cent. They found that strict mandatory restrictions on outdoor uses resulted in a relatively small reduction of 12 per cent.

Grafton et al (2015) used stochastic dynamic program to assess the social losses associated with the pre-emptive construction of the Kurnell desalination plant. Arguing that there is no ideal long term investment, they modelled the optimal augmentation under conditions of a scarcity price on water and contrast this outcome with that which occurred during the Millennial drought. They suggest that the premature water supply augmentation reduced the welfare of households by more than $3 billion.

In Melbourne, it was estimated that, as a result of water restrictions, households spend an estimated $1.078 billion. This expenditure involved $983 million for gardens, $36.1 million for pools/spas, and $35 million for commercial car washing (URS Australia, 2009). In addition, willingness to pay to avoid restrictions were estimated at: $233 per household or $197 million for Melbourne as a whole, to move from stage three to stage two restrictions; and $544 per household or $461 million for Melbourne as a whole to avoid stage four restrictions.

In addition, in 2016 Yarra Valley Water and the Centre for Water Policy Management at La Trobe University undertook a study on the *Estimated Residential Price Elasticity of Demand for Melbourne*. This report used a price increase of 21.7 per cent, plus the consumer price index, that occurred in 2013-14 to estimate the elasticity of residential demand for water. This study involved 715 households over 16 quarters from quarter three in 2011 to quarter two in 2015. A range of functional forms were examined and they found that price elasticities range from -0.3 to -0.13 suggesting inelastic demand in line with other studies.

What price to use?

A significant issue for the literature has been on the econometric issues associated with complex tariff systems that frequently exist for urban water supplies (Hewitt and Hanemann 1995; OECD 1999). Water supply tariffs generally have to meet multiple, often conflicting, objectives of equity, revenue neutrality, simplicity, community acceptance, efficiency and encouraging conservation of the resource. This raises questions: should average or marginal prices be measured? Inclining block tariffs result in effective subsidies for water consumption between parties, and how should the actual price that consumers face be estimated?

There was considerable early support for average prices in estimating water demand (Billings and Agthe 1980; Hogarty and Mackay 1975), in part because it was argued that this is what consumers experienced and in part because it is easier to calculate. Other estimates of appropriate prices have included: incorporating both average and marginal costs (Opaluch 1982 and 1984), adding “Shin prices” which purport to represent the prices consumers face (Shin, 1985, Nieswiadomy and Molina, 1991 among others), or subtract the marginal price from the average price (Chicoine *et al*., 1986 and Griffin and Chang, 1990).

However, Taylor et al. (2004) showed that the empirical support for average prices being the most appropriate was an artefact of the fixed fee aspect of a water bill. When a fixed fee exists then the improved goodness of fit for the average price formulation results from the unitary elastic identity created when the price schedule includes a fixed fee than an empirical confirmation of consumer behaviour. They found that once fixed fees were removed from their sample, the marginal price specification generated an improved statistical fit and a less-elastic demand function.

The functional form of demand

An important issue to consider is what functional form should be used to estimate the interactions between price and quantity demanded. The choice of functional form is not neutral. For instance, in the meta-anlaysis conducted by Espey et al (1997) and Dalhuisen et al. (2003) include a dummy variable for log linear specifications in their analysis and found that, with all else being equal, a log linear specification may result in a less elastic estimate. Under the most commonly used functional forms, the water demand function will exhibit different elasticities at different levels of use and in different price ranges. In fact, the same demand curve can be elastic in some ranges and inelastic only in other ranges.

There are five functional forms for demand elasticity that have predominately been used in the literature (Monteiro and Roseta-Palma, 2011). These are:

Linear	$D = ap + b\theta + c\emptyset' + dz' + f$
Double-log	$e^D = ae^p + be^\theta + ce^{\emptyset'} + dz' + f$
Semi logarithmic (log-lin)	$e^D = ap + b\theta + c\emptyset' + dz' + f$
Semi logarithmic (lin-log)	$D = ae^p + be^\theta + ce^{\emptyset'} + dz' + f$
Stone-Geary	$D = (1 - \beta_d)\gamma_d + \beta_d \frac{\theta}{p} + c\emptyset' + dz'$

Where *D* is the quantity of water demanded and *p* is the water price, θ stands for income, $\emptyset'$ represents weather variables such as temperature and precipitation, *z* is a vector that can include any appropriate household attributes, while *a, b, c, d, f, g*, and *h* are parameters. In the Stone-Geary specification, β_d stands for the fixed proportion of the supernumerary income spent on water (the residual income after the essential needs of water and other goods have been satisfied), and γ_w stands for the fixed component of water consumption (unresponsive to prices). The Stone-Geary is explained more below.

In Australia, the lin-log structural form has been used extensively (Hughes et al 2009, Grafton and various collaborators in their models of the Sydney water supply system, and the Centre for International Economics (2010)). These studies have adopted variations of the form:

$$D = a_1 p^{-\varepsilon_1} + a_2 p^{-\varepsilon_2}$$

Where a_1 and a_2 are parameters for indoor and outdoor water use respectively, and ε_1 and ε_2 are the associated elasticities.

Critically, this functional form was used in the work that was used to determine the Kurnell desalination plant operating arrangements. In that study, and the subsequent research of Grafton and various collaborators, the values for those parameters were given as:

$$a_1 = 0.0539$$

$$a_1 = 0.0021$$

$$\varepsilon_1 = 0.216$$

$$\varepsilon_2 = 0.59$$

Which means that a one per cent in price results in a 0.216 per cent decline in indoor water use and a 0.59 per cent decline in outdoor water use.

Monteiro and Roseta-Palma (2011) showed that demand becomes less elastic with higher consumption for most functional forms. Only the double-log case is associated with constant elasticity while the Stone-Geary specification is indeterminate as it depends on the actual values taken by the variables and associated parameters.

Worthington and Hoffman (2008) point out that despite the apparently extensive literature on water demand, many of these models reuse information and, in reality, much of the evidence is reliant on only a few unique data sets. This matters because, even though there is considerable broad agreement about the responsiveness of demand to price, the section of the demand curve being measured is limited. As a consequence, there are few data sets that incorporate catastrophic reservoir failure.

In addition, the assumptions that indoor water use is responsive to price has issues associated with the timeframe over that responsiveness and equity implications. For instance, Agthe and Billings (1987), Thomas and Syme (1988) and Renwick and Archibald (1998) have concluded that the price elasticity of residential water demand is lower for low-income households than middle- and high-income households

The Stone-Geary functional form can incorporate some minimum amount of water demand irrespective of prices. This effectively accounts for catastrophic reservoir failure. Gaudin et al. (2001) and Martínez-Espiñeira and Nauges (2004) used the Stone-Geary functional form to estimate water demand.

A Stone-Geary demand function assumes that there is a 'subsistence' quantity of a good that will be demanded irrespective of price. In the case of water, this subsistence level need not be associated with the minimum amount needed to live but with an amount that is conducive to life at a certain level of income (ie the amount can vary when income levels change dramatically). The Stone-Geary functional form for demand imposes very specific restrictions on a good being examined. These are that the good has: strong separability; the marginal propensity to consume (and thus income elasticity) is positive; and a quantity of demand that is inelastic. These assumptions are met when considering water demand, under the assumption that there is an essential for life component of demand for purposes such as drinking, cooking and hygiene.

To calculate the Stone-Geary demand function, consider a consumer who has a given level of income and prices. This consumer first purchases a subsistence level (γ_i) of each good i and then allocates the leftover income, (or supernumerary income) in fixed proportions to each good according to their respective preference parameter (β_s) (Deaton and Muellbauer, 1980; Chung, 1994). Let Q^w be the quantity of water demanded and Q^z is the quantity of all other goods demanded, while P^w and P^z are the prices of water and all other goods. Meanwhile, γ_w and $\gamma_z$are the subsistence levels of both water and all other goods. If we normalise the prices for all other goods, and arrange the budget constraint, we end up with a demand function for water where:

$$w = (1 - \beta_w)\gamma_w + \frac{\beta_w}{p}$$

As described above (while ignoring the income, weather and other variables that may influence discretionary demand). For a more detailed derivation of the Stone-Geary utility function for water refer to Martínez-Espiñeira and Nauges (2004).

As previously stated, the minimum for life may be approximately 20 litres per person per day, but a closer approximation for the minimum subsistence level in an industrialised country was given by Chenoweth (2008). This was 135 litres per person per day.

Appendix 2: Modelling Melbourne's water supply system

The MatLab model assumes known demands. The program runs water balance simulations for the monthly timestep, often the decision involves the notion of an "active" available water volume, which is the starting storage, plus inflows, less any evaporation, passing flow, other environmental flow and dead storage. Water allocated from any of the storages is always limited by the residual demand for the relevant part of the system; that is total demand less any water already supplied from elsewhere, recalling that demand is split between Cardinia Reservoir, Sugarloaf Reservoir and the remainder of the system.

- Water from upper Yarra Tributaries and Coranderrk Creek is harvested according to the harvesting rule supplied by Melbourne Water. This harvesting rule accounts for daily variation in flow interacting with the limited diversion capacity.
- Water is supplied from O'Shannassy Reservoir at a rate equal to the minimum of the active water volume and the transfer capacity.
- Water is supplied from Yan Yean Reservoir according to a special case rule to limit water drawn from this small storage. The rule reduces water used from Yan Yean when the whole system has high storage levels and/or when Yan Yean has low storage levels.
- Next Maroondah Reservoir, the Yarra Discharge at Yering Gorge, pumping to Sugarloaf Reservoir, and water supply from Sugarloaf are simulated. The sub-steps involved in this involve:
    - Determining harvesting from Graceburn into Maroondah;
    - Determining a first estimate of spills from Maroondah using a rule supplied by Melbourne Water, which is required as Maroondah is small compared with inflows and hence can spill within the month but not be full at the end of the month;
    - Determining the active volume available from Maroondah;
    - Determining the aqueduct flow to Sugarloaf Reservoir as the minimum of the active volume and aqueduct/pump capacity;
    - Estimating the flow at Yering Gorge, including any requisite passing flow released from Upper Yarra reservoir and all spills and releases from upstream points, except spills from Upper Yarra. If there is insufficient water in Upper Yarra to supply the required passing flow at Yering Gorge, water is taken from Maroondah if available there;
    - Determining the pumped volume from the Yarra to Sugarloaf, with a harvesting rule supplied by Melbourne Water;
    - Adding water from the North-South transfer to Sugarloaf (and to other demands if Sugarloaf is full and only in scenarios and situations considering the North-South transfer);
    - Supplying the demand from Sugarloaf;
    - Checking the pumping and aqueduct transfers can be accommodated in Sugarloaf. If not these are reduced, with the preference given to reducing the pumping from the Yarra;
    - Finally the Maroondah Reservoir water balance is recalculated
- Next, Tarago Reservoir is simulated. It is assumed that 94% of inflows are available to Melbourne Water and the remainder are released immediately. The Tarago demand is assumed to be constant volume.
- The active volume at Upper Yarra and Thomson are then estimated.
- Cardinia Reservoir is simulated next with a transfer from Upper Yarra Reservoir (via Silvan in reality) determined based on the objective of maintaining the Cardinia storage at 242 GL (86%) and limited by the transfer capacity and available water in Upper Yarra and Thomson. If the desalination plant is operating and Cardinia becomes full, it is assumed that the excess water is pumped to Silvan Reservoir and reduces the demand on Upper Yarra Reservoir.

- Upper Yarra Reservoir is simulated next and supplies the system wide residual demand with transfers from Thomson to Upper Yarra to maintain level, limited by transfer capacity.
- Thomson reservoir is then simulated.
- A series of adjustments are then made if either Upper Yarra or Thomson is above a level at which transfers should be maximised and there is space available in Cardinia Reservoir and capacity in the transfer system to move additional water.

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