The economic value of water in storage

Selected excerpts

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Abstract

The advent of financially feasible climate independent water supply sources that can be built within system memory timescale changes the optimal release strategy available for a reservoir. Climate independent water supply sources, such as reverse osmosis desalination plants, have very different reliability and cost profiles than gravity fed reservoirs and so influence optimal release strategies significantly. They also provide an alternative to reservoir failure. This study will examine how the optimal release strategy changes with the introduction of an augmentation option and in the presence of an existing climate independent water supply source.

Optimal release strategies, which establish the economically efficient trade-off between consuming or storing water, have been extensively examined in the literature, involving various levels of complexity, and with alternative engineering constraints considered and have accounted for hydrological risk in different ways. Explicitly or implicitly, they involve trading off the cost and probability of reservoir failure with current and future consumption of water as the reservoir management problem has been conceptualising as consuming water today or holding it in storage for future consumption. With the ability to construct climate independent water supply sources, this decision is now whether to consume water today, hold it in storage for tomorrow or to start constructing additional supply sources today for future consumption.

Economic efficiency is achieved when the marginal benefit of consuming water is equalised across the planning timeframe, defining the optimal release strategy. While there is an extensive academic literature examining urban water demand, particularly price elasticity and also, to a lesser extent, income elasticities there is little to no empirical evidence on consumers’ willingness to pay for very basic levels of service. The only significant industrialised city to experience an almost complete failure of its water supply system is Cape Town (Sagris et al., 2018). This means that there has been no empirical evidence available data about consumers’ willingness to pay for essential for life water services, a critical input in determining an optimal release strategy.

This study will quantify how the expected social benefits of an optimal release strategy change when a climate independent augmentation option is available. It examines the features that determine the optimal augmentation trigger for a climate independent water supply source, and how hydrological risk influences this trigger. It will propose a security cost function reflective of the key variables in the augmentation decision, specifically the level of hydrological risk, the timing of an augmentation, and the level of service that defines reservoir failure. This has been lacking in past determinations of optimal release strategies and from regulatory frameworks governing the operation of water supply systems.

1 Hydroclimatic understanding of water supply system risk

‘Life is full of risk,’ and while infrastructure can reduce risk, it cannot completely eliminate all risk (Gibson, 1976). Technology can acerbate these risks but can also be the source mitigating them as well. When it comes to water supply systems, they have finite capacity to supply water due to a range of factors, particularly hydrological variability. The S-Y-P relationship described by hydroclimatic scientists attempts to quantify the relationship between an uncertain naturally occurring hydrological resources and the yield produced by reservoirs (Taylor et al., 2017). Due to industry practice, hydroclimatic scientists have focused on supplying a desired yield with the assumption that the reservoir operator has the discretion to vary the amount supplied in periods of relative shortfalls.

The hydrologic risks of water supply systems are typically measured and regulated against long-term performance measures, such as the vulnerability, resilience and, most importantly, reliability of a reservoir (McMahon, et al., 2007b). Technological advances have made it possible to introduce climate independent water supply sources within system memory, changing the risk profile of the water supply system and, if the operating rules adjust to new water supply sources, of individual reservoirs. This PhD examines how climate independent water supply sources alter the risk of reservoir failure, how it represents an alternative to failure and how incorporating it into the optimal release strategy changes how much, and at what price, water to release at every level of storage.

Historically hydroclimatic scientists have defined reservoir risk in the context of long-term performance, where the initial conditions of the reservoir are not relevant. This is because a key challenge to determining the available hydrologic resource is the variability of hydrological systems that exhibit cyclical behaviour that can stretch from seasonality to multi-decadal (Hurst, 1951). For instance, in south-east Australia rainfall is highly variable as even the national anthem describes it as a land of droughts and flooding rains. Rainfalls are influenced by uncertain climate patterns that can range from five to seven years, in the case of the El Nino influence, and the multi decade Pacific Oscillation which can last for 20 or 30 years (Kiem, 2004).

To account for the cyclical nature of naturally occurring hydrologic resource, hydroclimatic scientists have examined the relationship between the storage size, demand on the reservoir, and the confidence that the demand can be supplied in a long-term context. Consequentially, regulators have interpreted that risk into level of service obligations for water utilities to operate towards and as the basis of long-term augmentations. However, the ability to build climate independent water sources in time frames significantly shorter than the system memory of a reservoir represents an opportunity to limit social losses associated with water shortfalls. This necessitates incorporating a short-term perspective of risk into the operation and augmentation of water supply systems.

Rather than experiencing ‘catastrophic’ reservoir failure, as an inability to meet high economic valued water has been referred (Hashimoto et al., 1982), a desalination plant can be built if the decision to augment the water supply system occurs early enough. The reduction in time required to deliver modern climate independent supply options, compared with the time required to build a reservoir and for it to fill under uncertain inflows, allows a significant change in mindset around developing and operating water supplies. On one hand, a desalination plant could be built. On the other, this may be unnecessary or pre-emptive augmentation for which there is an economic cost. The challenge is that such decisions need to be made with uncertainty as to future outcomes.

1.1 Defining reservoir performance

The study of reservoir behaviour has revolved around the related questions of:

1. How much yield at a given level of reliability can be achieved for a given capacity; and

2. What is the design capacity of a single reservoir for meeting a given yield and reliability?

Reservoirs for Australian capital cities, and most of the developed world, have gone through the full design-optimisation process and construction with the final build reflecting based on local characteristics, operating procedures, and other factors influencing the final size (McMahon, 2008). So, the task in Australia, and most of the developed world, isn't defining the optimal size of a reservoir but understanding how it behaves and what is potential performance, in terms of delivering water, is like.

Hydroclimatic scientists use three main terms to describe the performance of reservoirs reliability, vulnerability and resilience (Hashimoto et al., 1982). These methods of assessing the S-Y-P relationship are the basis of forming appropriate operating rules for reservoirs and for selecting reservoir capacities, system configurations, operation policies, and targets (Hashimoto et al., 1982). Since regulations are intended to underpin long-term investments, regulators typically use long-term expectations of reliability to inform the design criteria, or service level obligations. These regulatory frameworks are established from analysis of system performance under stationary hydrologic conditions, sometimes with growing demand. As an example, the *Water Security Program 2016-2046* Department of Natural Resources, (2016) detailed the level of service (LOS) requirements of Seqwater as:

1. The bulk water supply system will not reach the:
    a. trigger for medium level restrictions more than once in 10 years on average; and
    b. trigger for the essential minimum supply volume level (EMSV), or the level at which only the EMSV can be provided, more than once in 10,000 years on average.
2. Wivenhoe Dam, the Baroon Pocket Dam and the Hinze Dam will not reach its minimum operating level more than once every 10,000 years.
3. Medium level restrictions will last no longer than one year on average.

Long-term inflow expectations are used to set drought responses as well as forming the basis of pricing for water reservoir operators.

1.2 Optimal release functions and drought response

A key challenge to determining the available resource is the variability of hydrological systems and the deep uncertainty about future inflows. Drought is also a "creeping phenomenon" (Gillette, 1950), which alludes to how challenging it is to determine if the hydrologic inflow is experiencing a cyclical downturn or there are drought conditions, making an accurate prediction of either its onset or end a difficult and contested task. According to (Tannehill, 1971), "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."

With prices fixed, urban utilities are required to imposing qualitative restrictions on the amount of water that can be used for different purposes to balance supply and demand (Quiggin, 2006). The long-term steady state expectations of naturally occurring hydrologic resource have been used to establish restrictions regime and broader drought responses that attempt to balance the available water with demand (Draper & Lund, 2004). hydroclimatic scientists refer to the problem of how much water to withhold from consumption today so it may be available tomorrow, effectively the restrictions regime of a reservoir, as ''hedging'' (Bower et al., 1962).

Hu et al., (2016) developed a two-stage hedging regime that utilised expected inflows, in addition to current water in storage, as the basis for operating rules. This contrasts with the most commonly used triggers, according to (Shih & Revelle, 1994) which typically are based on the level of water available, defined as the level of water in storage plus expected inflows (Bayazit & Ünal, 1990). Shih & Revelle, (1994) argued that using storage augmented by expected inflows results in potentially more reasonable behaviour. However, (Shiau & Lee, 2005) found that hedging is ineffectual if it is just based on water in storage as there is no predictive component anticipating future need. Hu et al., (2016) recommended a two-stage model to reduce the uncertainty associated with forecasts of water availability.

Hu et al., (2016) showed that extending the two-period model to a multiperiod one results in utility being optimised across all periods. The capacity constraints represent the shadow prices for investing in augmentations or expanding constraints in the water supply system. The perfect foresight of deterministic models understates the value of new storage and can underestimate the actual scarcity in the system, and the subsequent optimal scarcity price to ration water availability (Pulido-Velazquez et al., 2004). Pulido-Velázquez et al., (2006) observed that having all water allocated with perfect foresight of hydrological outcomes creates an assessment without transaction costs or risks.

1.3 Urban water supply pricing

Arguably long-term reliability assessments guide the level of investment in water supply infrastructure through the use of long-run marginal costs (LRMC) to send a price signal on future investments. The Victorian Essential Services Commission, (2005) and National Economic Research Associates, (2012) defines LRMC as short-run marginal cost (SRMC) plus marginal capital costs, where marginal capital costs measure the marginal increase in expected future supply augmentation costs associated with an incremental increase in demand.

Consider the NSW water pricing regulator, the NSW Independent Pricing and Regulatory Tribunal (IPART), which sets the maximum retail price for water in Sydney. Historically this price has been set according to the long run marginal cost of water supply (LRMC), with prices fixed between price determinations. In its most recent price determination, IPART stated that they set water usage prices based on the long-run marginal cost (LRMC) of providing water. They said:

> “LRMC promotes efficient water usage and investment decisions to the extent that it signals the costs of supplying water to meet demand over the long-term which are predominantly the costs of bulk water supply augmentation measures. It also provides a price signal to conserve water and encourage the development of substitutes such as recycled water.” (IPART, 2020, page 305).

This approach has been common across Australian regulators and in other jurisdictions (Howe, 2005).

Economists argue that if the price of water does not provide incentives to reflect its scarcity, then consumers will not adjust their behaviour when the supply is in short supply or is abundant (see Ng, (1987) Griffin, (2001), or Grafton & Kompas, (2007) among a wide range of others).

In order to reflect the additional costs associated with drought conditions, IPART’s most recent pricing determination deviates from past pricing decisions having the price influenced by storage levels (IPART, 2020). Drought conditions create additional costs for a water supplier, such as advertising restrictions regimes, operating the pre-existing desalination plant in Sydney, undertaking water conservation projects and the inter-basin transfer from the Shoalhaven. IPART’s pricing decision will allow these costs to be recouped if storages fall below 60 per cent. The result is that when dam levels are above 60 per cent, the price of a kilolitre of water is $2.35, but this price rises to $3.18 if dam levels fall below 60 per cent.

1.4 What happened during the Millennial drought

The advent of reliable climate independent water supply sources that can be built relatively quickly, compared to many reservoir options, provides an alternative means of managing short-term risks to the water supply system. Rather than experiencing ‘catastrophic’ reservoir failure a desalination plant can be built within system memory. The reduction in time required to deliver modern climate independent supply options, compared with the time required to build a reservoir and for it to fill under uncertain inflows, allows a significant change in mindset around developing and operating water supplies. With climatic variability, even highly reliable reservoirs, with significant “excess” storage capacity, can require augmentations during periods of prolonged low inflow.

During the Millennium Drought (Heberger, 2012) in southeast Australia (2001-2009) despite Melbourne's water supply system had been deemed to be sufficient for the foreseeable future in 2004 (Victoria's Department of Sustainability and Environment., 2004)) and 2005 (CSIRO, 2005). Then, in 20007 an assessment of the reserve capacity of the water supply system suggesting the city required 240 gigalitres in augmentations by 2012. Consequentially:

> "the Bracks Labor government in June 2007 announced a plan to spend heavily on two new water projects: the largest desalination plant in the southern hemisphere; and a pipeline to bring water to Melbourne from across the Great Dividing Range…" (Edwards, 2012)

The Millennium Drought (van Dijk et al., 2013) was different to most previous droughts in that it covered the majority of east coast of the Australian continent and lasted for over a decade (Heberger, 2012). So, in addition to Melbourne's emergency augmentations, a range of urban water supply systems that were deemed to be sufficiently reliable at the start of the drought were augmented through the addition of desalination plants (Productivity Commission, 2011). Since these water supply systems were considered to have sufficient long-term reliability, no planning for augmentations was undertaken prior to the emergency decision being made. Consequentially, the augmentations were larger, and potentially more expensive, than otherwise would have been required.

Consider the response of water authorities in California. Facing reduced inflows and uncertain future water supplies, there was a total of 21 proposed desalination projects in 2006. This number had fallen to 19 in 2012 and, as of May 2016, was just nine (Cooley et al., 2006). That all these projects were not implemented suggests that may have been short-term responses to the risk of short-term supply shortfalls and, as expectations of future inflows changed, the projects were not deemed to be necessary.

The policy choice facing reservoir operators is no longer whether to supply water today or reserve it for higher economic value purposes tomorrow. Instead, it is whether to supply water today, reserve water for tomorrow or augment the water supply system so that in the near future a climate independent water supply source will be available. The challenge for the reservoir operator is to ensure that they do not augment pre-emptively and invest significant capital unnecessarily.

4 Optimal release states

The issue of optimal resource consumption has been extensively analysed in economics in a range of areas, including water resources. Economic theory suggests that a resource is being used efficiently if the cost of obtaining and consuming it is equivalent to the benefit to society of consuming the last unit, which is why determining the optimal release strategy of a reservoir is important. The marginal cost of water should represent the full cost of water. This means that the cost to the consumer should include the cost of operations, capital replacement, environmental costs, augmentation and the opportunity cost of using water today (Zetland & Gasson, 2012). The optimal release strategy shows how to maximise the benefits of the scarce water resources while also minimising the costs associated with delivering it to consumers. This chapter describes the objective functions that allow for optimisation, depending on the nature of the water supply sources available.

Irrespective of the approach to defining optimal releases, the decision has been considered as a trade-off between consumption today versus consumption tomorrow. The advent of climate independent water supply sources that can be built within system memory timescales complicate this decision. When facing uncertain future supplies, urban reservoir operators in Australia and the United States have augmented their water supply systems rather than experience failure. In less industrialised areas of the world, for instance Sao Paulo Brazil, restricted access to water may be met through providing intermittent supply. For the purposes of this chapter, the response of wealthy industrialised nations will be considered. It is suggested that the trade-off a reservoir operator confronts is:

- How much water to consume today;
- How much water to remain in storage for tomorrow;
- Whether to augment the water supply system to avoid reservoir failure; and
- If a climate independent water supply source is already present, then there is a discrete choice to operate it as well. This can be significant if it has substantive start-up costs.

Having the capacity to augment a water supply system means that the short-term operation of the reservoir has significant implications for future investment. This is particularly true if reservoir operators prefer to augment a water supply system rather than experience reservoir failure. The capacity to augment a water supply system, rather than experiencing reservoir failure, suggests that the empirically undefined social cost functions could be approximated with engineering costs associated with augmentation options. This chapter will examine how the outcomes of an optimal release strategy change with the ability to augment the water supply system with a climate independent water supply source. It will also examine how an augmentation option changes the optimal resource allocation decisions and how to determine when to access water from it.

6 Cost minimisation and the security function

The benefit maximising approach favoured by economists uses the water supply system specifications, particularly the demand curve and the assumptions about risk. to determine appropriate trade-offs between consumption today and tomorrow. The focus is on maximising the social benefit from consuming the resource. This includes balancing the risks and payoffs of the naturally occurring resource with the costs of manufacturing it. The result is an optimal release strategy that varies with the level of water available. In the benefit maximising model either the quantity of water released, or the price of the water released, is used to obtain the optimal release strategy, implying water can be varied period by period to reflect the scarcity of the resource.

Many water utilities, particularly in Australia, do not use scarcity pricing. Instead, they ration the available water through restricting the amount supplied. With prices fixed, urban utilities are required to imposing qualitative restrictions on the amount of water that can be used for different purposes (Quiggin, 2006) to balance supply and demand. The long-term steady state expectations of naturally occurring hydrologic resource have been used to establish restrictions regime and broader drought responses that attempt to balance the available water with demand. Having a fixed target demand is typical of the approach adopted by hydroclimatic scientists (Harou et al., 2009). It is also the approach adopted by water regulators to match long-term expectations of water availability, demand and infrastructure investment. Consequentially, regulators have interpreted that risk into level of service obligations for water utilities to operate towards and as the basis of long-term augmentations.

This chapter is examining how a climate independent water supply source changes the optimal release strategy for a reservoir operator attempting to supply a fixed quantity of water. While the optimal release defined in Chapter 5 could have the price or quantity of water released varied by 0.01 increments, in this chapter the quantity released can only be varied to set quantities reflecting a restrictions regime. The model examined in this chapter also includes a short-term reliability constraint reflecting the socially acceptable level of risk acceptable over the time it takes for the construction of the augmentation. The following literate review will examine how to incorporate the risk of failure into a model of a water supply system. The literature review and Chapter 1 has a discussion on how reliability has been defined and translated into levels of service for operating a water supply system.

6.1 Literature Review

There are different ways to incorporate reservoir failure into a model. In Chapter 5 a loss function was added to the demand function to represent heightened risk aversion for certain quantities of water. In addition, the elasticity of the demand curve was altered to evaluate the consequence for the optimal release function. This chapter will examine a cost-minimisation model to determine the optimal release function for a reservoir with a novel treatment of short-term risk that is combines a loss function with a reliability constraint. Two methods of defining short-term risk are considered in this chapter, and a scenario of a higher variance is developed to examine its implications of the reliability constraint on the optimal release.

6.1.1 Hydrologic risk definitions

Reliability is typically expressed as the probability that a water supply system can meet a target demand (Klemeš et al., 1981). The definition of reliability, outside of the United States, is based on the steady state probability of a system failure where failure is defined as the inability of the system to deliver a desired amount of water (Vogel and Bolognese 1995). Urban water utilities use level of service obligations that meet a defined level of reliability. Augmentations, or interventions such a restrictions regime, are imposed in order to achieve these level of service obligations. See, for instance Queensland government, (2013):

- Melbourne: 95 per cent reliability of supply with no longer than 12 consecutive months of water restrictions that are no more severe than stage three;

- Canberra: restrictions should not occur more than one year in 20, with a severe water restrictions target of 150 litres per person per day (which is about a 45 per cent reduction in summer water demand); and
- Sydney: reliability comprises security (defined as water storage not falling below 5 per cent of water storage capacity more often than 0.001% of the time), robustness (restrictions occur no more than once every 10 years on average) and reliability (restrictions have limited duration) measures.

In the United States, the definition of reliability leads to estimates of the firm yield, a term which describes the yield that can be met over a particular planning period with a specified no-failure reliability. The firm yield is defined as the maximum yield that can be serviced from the reservoir through the drought of record (Waldron & Archfield, 2006). This is related to the reliability-based approach but considers a different dimension of the S-Y-P relationship. The safe yield concept means that water utilities can plan for explicit risk levels for different classes of water use, for instance, high reliabilities for uses essential to public health (Howe, et al., 1994).

A reliability standard does not describe the relationship between water available, price and the amount of water demanded by consumers. Rather it specifies a discrete level of water, the level of service to be met, and the socially acceptable level of failure, α, that defines the reliability of the water supply. See Figure 3-1 for the reservoir operator's operating rule represented.

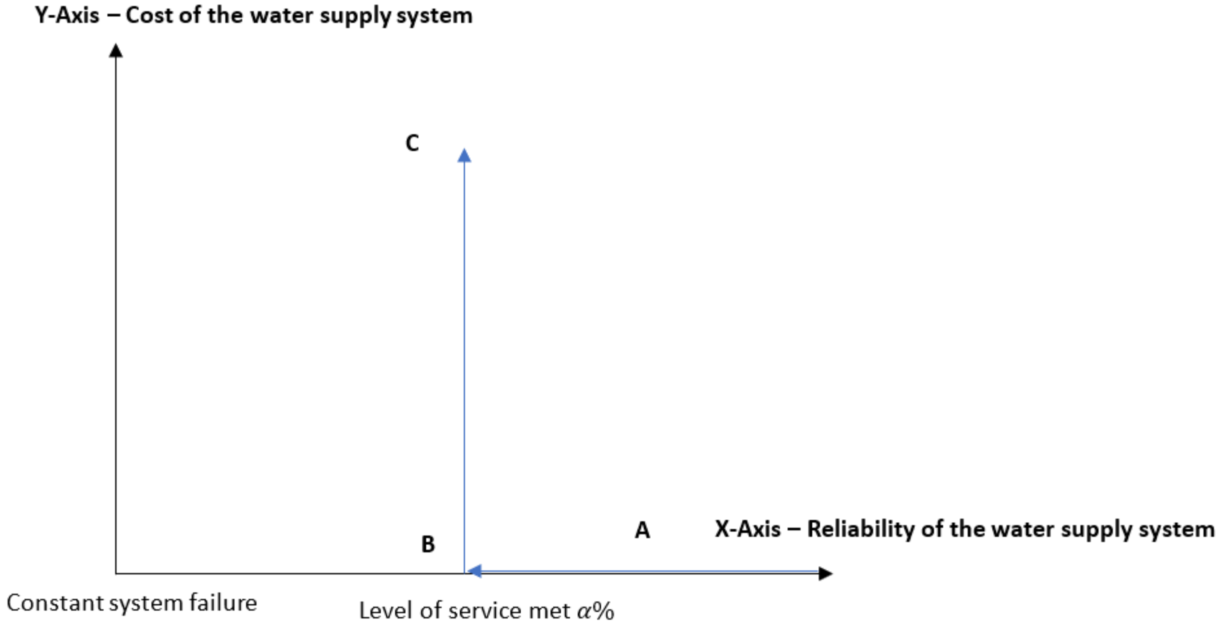

Figure 3-1: Willingness to improve reliability under the reliability constraint outlined in the total cost minimisation model

Using a reliability constraint as a means of incorporating social risk preferences suggests an unusual demand curve for risk. In Figure 3-1 it goes from point A, where reliability is higher than the socially acceptable level of risk and there is no reason to invest additional resources to improve reliability, to point B, where the reliability constraint is just satisfied. At point B the reliability constraint implies that society is willing to invest any level of resources to maintain reliability at that point. A reliability constraint, or level of service obligation, implies that society is indifferent to increasing risk while the level of service obligations are met. At the point where the level of service just fails to be met, society is willing to pay any amount to maintain risk at that level. Since reliability is defined in the long-term, as a steady state probability of being able to meet expected demand with a given level of probability, α, the reservoir operating rule is based on long-term expectations. Water supply systems are augmented to maintain a level of reliability, in the long-term, but are naïve to short-term risk.

The investment in a water supply system's reliability could be considered in balance, by this approach, when the long run reliability is equivalent to α. This will be dependent on the variability of water supplies and not on the relationship between the marginal benefit of consuming water and the marginal cost of additional augmentations.

A reliability constraint also focuses on delivering a specific quantity of water with consistency. Since reliability is defined in the long-term, as a steady state probability of being able to meet expected demand with a given level of probability, α, the reservoir operating rules are based on long-term expectations. In theory water supply systems are augmented as the level of reliability, in the long-term, but are naïve to short-term risk. Complicating matters further, the assessment of long-term reliability is, inevitably, conducted with reservoirs full. In practice water supply systems tend to be augmented during droughts, when short-term risks are unacceptably high.

6.1.2 Proposed stylised short-term reliability constraints

Long-term reliability is important for sizing reservoirs and determining the optimal release strategy. Historically there has been little that could be done during a drought other than restricting supply to mitigate the risks of insufficient naturally occurring hydrologic resources. However, the ability to build climate independent water supply sources within water supply system memory means that there is an alternative to imposing restrictions on water consumers.

Having this option available means that short-term risks can be incorporated into reservoir management. These short-term risks represent the risk of not being able to supply a specific quantity of water over the construction timeframe of an augmentation option. This can be described by the following stylised reliability constraint:

$$Pr_{i,t}\left(S_t + \sum_{t=t}^{t+t_{lead}}(\ In_{t,i} - Q_{t,min}) < Q_{min}\right) = \alpha \qquad (3\text{-}1)$$

where $Pr_{i,t}$ is the probability of inflow amount *i* in period t, t_{lead} is the lead time required to build the augmentation, and Q_{min} is the minimum level of service and α is the socially acceptable level of risk. It should be noted that α is a probability that, when combined with an expectation of the inflow distribution and the quantity of water being targeted, gives a quantity of water that must be kept in storage. Equation (6-1) is attempting to replicate the level of service obligations that are generated by the S-Y-P relationship for *short-term risk* where the short-term is the length of the construction time of an augmentation. This period is important as it represents the time it takes to respond to low water levels and to maintain minimum levels of service.

The short-term reliability constraint described by Equation (6-1) effectively says that the reservoir operator needs to augment if the risk of not being able to supply a target quantity of water, Q_{min}, is more than the socially acceptable level of risk. That is to say, that the α term gives the probability that water will not be available over the augmentation construction timeframe. It is a short-term measure, as it does not define a long-run expectation of system failure. This chapter will examine how the level of socially acceptable risk influences the cost of maintaining a water supply system.

Consequentially, given the short-term reliability constraint described in Equation (6-1), there is a level of storage at which an augmentation is triggered, called S_{aug}. Given the characteristics of the water supply system, it may be optimal to augment it when storages are above S_{aug}. However, when storages are at or below S_{aug} then the decision is out of the reservoir operators' hands and the augmentation has to be built.

It should be noted that the reliability constraint could be written as a sequence of the lowest inflows over the augmentation timeframe on record, worst drought of record of length of the augmentation timeframe, or some combination of the above. It is expressed as Equation (6-1) to provide a clear probability measure of short-term risks.

The approach of combining the loss function and reliability constraint is chosen for three reasons. The first is that the reliability constraint is a stylised representation as to how water utilities operate their water supply system, such as the level of service obligations based on defined S-Y-P relationships. The second is that the loss function represents the penalty that is incurred if the minimum level of service is violated. Thirdly, empirically establishing consumer risk preferences is challenging given the infrequency of urban reservoir failure.

6.2 Method

In this chapter, the objective of the reservoir operator is to minimise costs over the model timeframe. The reservoir operator has a limited set of quantities of water that can be released, representing using restrictions to ration the available water resource. This cost minimisation is subject to the costs selected for inclusion in the model. It is also subject to water mass balance constraints and the short-term reliability constraint defined in Equation (6-1). Costs include both the physical costs of delivering water, operating a pre-desalination plant or augmenting a water supply system. Also included are the social costs of foregone consumption that are incurred when restrictions are imposed. The short-term reliability constraint examines how the optimal release strategy for a cost minimisation model changes as social risk preferences are adjusted. The cost minimisation model is solved in a similar manner to the benefit maximising model examined in Chapter 5, with the application of the Bellman Equation to a stochastic dynamic program.

In practice reservoir operators do not necessarily have explicit target demands, and households can vary the amount of water they consume. However, regulatory pricing structures are built around target demands (Independent Pricing and Regulatory Tribunal, 2022). The model adopted in this chapter attempts to approximate this approach.

In this chapter, it is proposed that the reservoir operator's policy choice is how much water to allocate in a period. In Chapter 5 the reservoir operator had 101 alternative quantities of water to release whereas in this chapter the reservoir operator will ration water through restrictions, meaning that they will either meet the target demand or meet a restricted component of the target. There are a limited number of levels of restriction that can be imposed. The reservoir operator can also decide to operate the existing desalination plant or to expand it. However, if the level of storage is at or below the reliability constraint, then the augmentation is automatically triggered and is outside the policy choice of the reservoir operator. This means that the model will optimise the restrictions regime, the operation of any climate independent water supply sources and the augmentation decision, subject to the short-term reliability constraint not being binding. If the short-term reliability constraint is binding, then the augmentation decision is automatically undertaken and is outside of the reservoir operator's policy choice. The model will then optimise the restrictions regime and the operation of all climate independent water supply sources available.

The foregone consumption, defined as a cost incurred in operating the water supply system when restrictions are imposed, is associated with how much water supplied is constrained from the target quantity. It is defined as

$$TC_{x,i}(Q_i) = TB(\bar{Q}) - TB(x * \bar{Q}) \qquad \text{where } Q_i = x * \bar{Q}, 0\ otherwise$$

$$TC_{y,i}(Q_i) = TB(\bar{Q}) - TB(y * \bar{Q}) \qquad \text{where } Q_i = y * \bar{Q}, 0\ otherwise$$

$$TC_{z,i}(Q_i) = TB(\bar{Q}) - TB(z * \bar{Q}) \qquad \text{where } Q_i = z * \bar{Q}, 0\ otherwise$$

Where $TC_{j,i}$ is the total cost function for the *j*th level of restrictions imposed in period *i*. The target quantity of water is defined as $\bar{Q}$. The total benefits of consuming water are defined by the total benefit function $TB(\bar{Q})$. The total benefit function associated with consuming water is defined as:

$$TB_i(Q_i) = A * \frac{(Q_i)^{1-B}}{1-B} - C * (Q_{min} - Q_i), for\ Q_i < Q_{min}\ else$$

$$TB_i(Q_i) = A * \frac{(Q_i)^{1-B}}{1-B} \tag{3-2}$$

Where *A, B,* and *C* are constants. This total benefit function is consistent with that used in Chapter 5.

The cost minimisation model can be described in the following equations:

$$\min_{x,y,z,In_{desal,1},In_{aug,i}} u = TC_t(Q_t) + TC_{t+1,i}(Q_{t+1,i}) \tag{3-3}$$

s.t.

$$TC_t(Q_t) = a_{delivery}(Q_t) + TC_{x,i}(Q_i) + TC_{y,i}(Q_i) + TC_{z,i}(Q_i)$$
$$+TC_{Q_{i<Q_{min}}}(Q_{min} - Q_{t,i}) + f_{desal}(In_{desal}) + f_{aug}(In_{aug}) + f_{\overline{aug}}(\overline{In_{aug}}) + f_{min}(Q_{min} - Q_{t,i}) \tag{3-4}$$

$$Q_i = \bar{Q}, x * \bar{Q}, y * \bar{Q}, \text{ or } Q_{min} - Q_i \tag{3-5}$$

$$S_t + Pr_{i,t}(In_t < Q_{min} = \alpha) * t_{lead} - Q_{min} * t_{lead} = S_{aug} \tag{3-6}$$

Where Q_{min} is the minimum level of service expected from the water supply system and $f_{min}(Q_{min} - Q_i)$ the costs associated with not meeting the minimum level of service quantity of water. If less than the minimum level of service is delivered, then $Q_{min} - Q_i$ is the difference between the quantity delivered in the period and the minimum level of service. The costs of producing water comprise the costs associated with supplying water and also any costs associated with operating the desalination plant or augmenting the water supply system. The cost of delivering water in the water supply system is $a_{delivery}(Q_t)$. The costs associated with operating the pre-existing desalination plant are $f_{desal}(In_{desal})$, while the capital costs associated with augmenting the water supply system is $f_{\overline{aug}}(\overline{In_{aug}})$, and the costs of operating the augmentation are $f_{aug}(In_{aug})$.

The current level of water in storage is S_t, while $Pr_{i,t}$ is the probability distribution of inflows in the current period. While inflows are unknown, the probability distribution they follow is known. The augmentation timeframe is t_{lead} while the level of storage at which the reliability constraint in Equation (6-1) is binding is described as S_{aug}.

Equation (6-6) describes the level of storage at which the augmentation is automatically triggered due to the reliability constraint described in Equation (6-1). It defines the amount of water that needs to be held in storage to meet the reliability constraint. The variable $Pr_{i,t}(In_t < Q_{min} = \alpha)$ defines the amount of inflow that is acceptable, given the socially acceptable risk tolerance defined by α. It should also be noted that Equation (6-6) is not summing a probability distribution. It is using a probability distribution to determine a specific level of inflows that can be anticipated with a given probability. It is the subsequent inflows that are summed.

The Bellman Equation associated with Equations (6-2) to (6-6) is:

$$V_{S_t} = \underset{\begin{bmatrix} S_t \leq 1 \\ \Pr(Q_t \geq Q_{min}) \geq \alpha \end{bmatrix}}{\underset{x,y,z,In_{desal,1},In_{aug,i}}{\min}} [TC_{x,i}(Q_i) + TC_{y,i}(Q_i) + TC_{z,i}(Q_i) + TC_{Q_{min}-Q_i}(Q_{min} - Q_i) +$$
$$TC_{aug,i}(Q_i) + TC_{desal,i}(Q_i)] + \beta V_{S_{t+1}}(S_t) \tag{3-7}$$

The value function will vary based on the level of water in storage in each period.

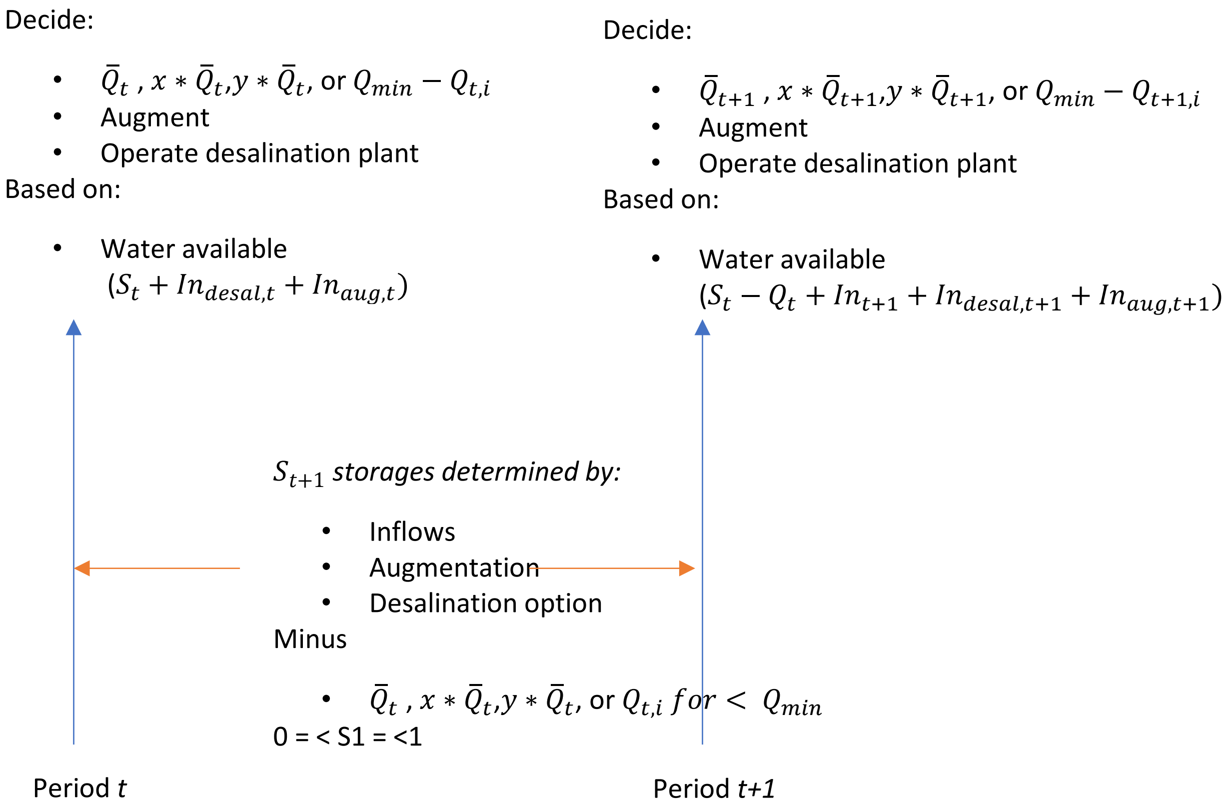

Figure 3-2: The policy choice being modelled

The policy choice in period *t* is to determine the optimal release, either $\bar{Q}$, $x * \bar{Q}$, $y * \bar{Q}$, or $Q_{min} - Q_i$, for the period. It can also involve augmenting the water supply system, or operating the pre-existing desalination plant if previously built, and whether to operate the pre-existing desalination plant. The decision is based on the total amount of water known to be available, which is the water in current storages the water available from the pre-existing desalination plant and the water available from the augmentation option if previously built, $S_t + In_{desal,t} + In_{aug,t}$. The maximum amount of water that can be released in one period is assumed to be 1.00. It is also assumed that this water is effectively withdrawn from the water supply system simultaneously and that inflow occurs over the period. The next period storage, *t+1*, is determined by the period inflows and the water mass balance described in Equation 5.8 and the constraint described in Equation 5.9. While not perfectly reflective of how water supply systems operate in practice it is intended to provide an approximation for the purpose of examining the trade-offs involve in storing or consuming water.

In applying the Bellman Equation to the models examined in Chapter 6, the states are the storage increments. These states are evaluated at each of the available levels of restriction. In addition, the choice of operating the pre-existing desalination plant or not doubles the number of states in that meeting the target demand, or meeting the level of each stage of restriction, can occur with or without operating the pre-existing desalination plant. Likewise, the choice of augmenting the water supply system again doubles the number of states, both with and without the water supply system having been augmented.

The stochastic dynamic programming will be applied to two total cost minimising models to examine how the optimal release function reflects how short-term risk is treated. The inflows are uncertain in this chapter. They also have the same level of variance as in Chapter 5 Model 5.3 and Scenario 5.A. The system considered includes a reservoir, existing desalination plant and the option to augment the system with expanded desalination capacity. The first model will examine the optimal release strategy for meeting a target demand with the least costs, with a relatively low variance, similar to that of Model 5.3, but including the constraint described in Equation (6-1). This optimal release strategy would be compared to the same model but with relatively higher variance in inflows, similar to the High variance model (Scenario 5.A).

Both Model 6.1 and Model 6.2 will examine the optimal release strategy for 101 storage increments. Consequentially, solving the model starts with determining the value of consuming water in the final period for every state. Given that there is no requirement to hold water outside the model planning timeframe, the optimal action in the final period is to consume all available water, which produces a known benefit according to Equation (6-6). This is calculated for all states of the model, with the calculations undertaken in R and described in Appendix 3. As in Chapter 5, the solution then proceeds backwards through the time periods solving the relevant Bellman Equation until the solution is complete.

The proposed models to be examined, Model 6.1 (Relatively low variance) and Model 6.2 (Relatively high variance), will use the Bellman Equation (6-6) to define the cost minimising optimal release function with a short-term social risk preference α. The acceptable level of social risk will be examined at levels 0%, 1% and 2%. The optimal release function, including desalination plant and augmentation option operation, augmentation trigger storages, implied price of water, net social benefits, total costs and costs associated with additional short-term security will be discussed for each model.

Note, there is only one possible augmentation over the timeframe modelled.

6.3 Problem formation

To examine how the optimal release strategy changes as the level variability in inflows changes, two models will be examined. The first (Model 6.1 Relatively low variance) will be a reservoir with a pre-existing desalination plant and an option to expand the water supply system with additional desalination capacity. There are also uncertain inflows of the same characteristics as in Model 5.3. The second model (Model 6.2 Relatively high variance) is the same water supply system but with the variance of inflows the same as Scenario 5.A. The policy choice is what price to place on the water to be allocated, or the quantity to release, either the target amount or impose a level of restrictions, whether to augment the water supply system and whether to operate a desalination plant or not.

The water supply system is the same as that examined in Chapter 5. The key differences between the water supply systems are that in this chapter a target demand is being met, with the capacity to impose restrictions. Additionally, if storages are below a certain point, S_{aug}, the reliability constraint is triggered, and the reservoir operator *must* augment the water supply system. Above S_{aug} the reservoir operator has the choice of augmenting the water supply system or not. Similar to Model 5.3, the reservoir operator also has the choice of operating a pre-existing desalination plant or not. There is only one augmentation option available to the water supply system operator.

Table 3-1: Cost minimisation model parameters (Models 6.1 and 6.2)

Variable	Symbol	Characteristics of variables	Normalised parameters
Inflow Model 6.1	$In_{i,i}$	Gamma	Assumed shape = 25 Assumed scale = 0.02 Variance $\sigma^2 = 0.01$ Mean $\mu = 0.50$
Inflow Model 6.2	$In_{i,i}$	Gamma	Assumed shape = 1.5625 Assumed scale = 0.32 Variance $\sigma^2 = 0.16$ Mean $\mu = 0.5$

Storage capacity	S_{max}	Total storage capacity (approximately 1,700,000 MLs)	1.000
Initial storage	S_0	There are 101 initial storage increments	Each storage increment represents 17,000 MLS
Target quantity of water	$\bar{Q}$	Fixed amount of water that reservoir operator is expected to meet	$\bar{Q} = 0.40$
Restriction level 1	x	First level of restrictions, reducing demand from target quantity by *x*	$x\bar{Q} = 0.38$
Restriction level 2	y	Second level of restrictions, reducing demand from target quantity by *y*	$y\bar{Q} = 0.36$
Restriction level 3	z	Third level of restrictions, reducing demand from target quantity by *z*	$z\bar{Q} \leq 0.30$
Total benefit function (Indoor use)	$A * \frac{(Q_i)^{1-B}}{1-B}$	$0.0021 * \frac{(Q_i)^{1-0.59}}{1-0.59}$	$3{,}570{,}000 * \frac{(Q_i)^{1-0.59}}{1-0.59}$
Marginal benefit curve (Demand curve)	$A * (Q_i)^{(-B)}$	$0.0021 * (Q_i)^{(-0.59)}$	$3{,}570{,}000 * (Q_i)^{(-0.59})$
Minimum service level	Q_{min}	Set at approximately half of the mean annual inflow (409,258 MLs)	0.30
Delivery costs	$a_{delivery,i}(Q_i)$	The cost to deliver one megalitre of water: \$3	The cost to deliver one storage increment (17,000 MLS): \$51,000
Q_{min} loss function	$f_{min}(Q_{min} - Q_{t,i})$	A flag fall cost of: \$1 billion A per ML less than Q_{min} cost: \$30,000	Flag fall cost: \$1 billion Per increment less than 0.30: \$510,000,000
Desalination cost	$f_{desal,i}(In_{desal,i})$	Start-up cost: \$0 Delivery cost: \$1,000/ML	Start-up cost: \$0 Delivery cost per increment: \$17,000,000
Augmentation cost	$f_{aug,i}(In_{aug,i}) + f_{\overline{aug},i}(\overline{In_{aug,\imath}})$	Operating cost: \$1,000/ML Annualised capital cost: \$75/ML	Operating cost per increment: \$17,000,000 Annualised capital cost per increment: \$1,275,000
Augmentation capacity	$\overline{In_{aug,\imath}}$	170,000 MLs/year	0.100
Discount rate	i	10%	
Discount factor	β	0.909	
Model timeframe	*N*	40 years	
Augmentation lead time	t_{lead}	*4 years*	*4 periods*

6.4 Results

6.4.1 Model 6.1 (Relatively low variance)

The policy choice for Model 6.1 (Relatively low variance) is to determine whether to meet the target demand or impose a level of restrictions. It is also whether to operate the pre-existing desalination plant, and/or expand the water supply system with the augmentation option, in order to meet the target demand or a level of restriction. Unlike the models in Chapter 5, the reservoir operator has the choice of releasing any quantity of water equal to or below the minimum service level, the third level of restrictions, or the three discrete values of restrictions level two, one or the target demand. There is not a free choice as to the quantity of water to be released, or the price to charge for the water.

The acceptable levels of short-term risk were examined at zero per cent, meaning that there needs to be sufficient water in storage to meet the minimum service level over the augmentation construction timeframe, and one per cent, meaning a one per cent chance of the system falling short of supplying water at the minimum level of service over the construction period. The zero-risk level implies augmentations at storages below 0.99 while the one percent risk level doesn't require augmentation at any storage above zero. When the socially acceptable level of risk is one per cent the initial level of storage that the reliability constraint is triggered at is lower than the optimal augmentation point. Consequentially, a one per cent socially acceptable level of risk produces an optimal release strategy equivalent to any socially acceptable level of risk that is higher than one per cent. The level of initial storage at which the reliability constraint is binding, S_{aug}, is described in the figure below.

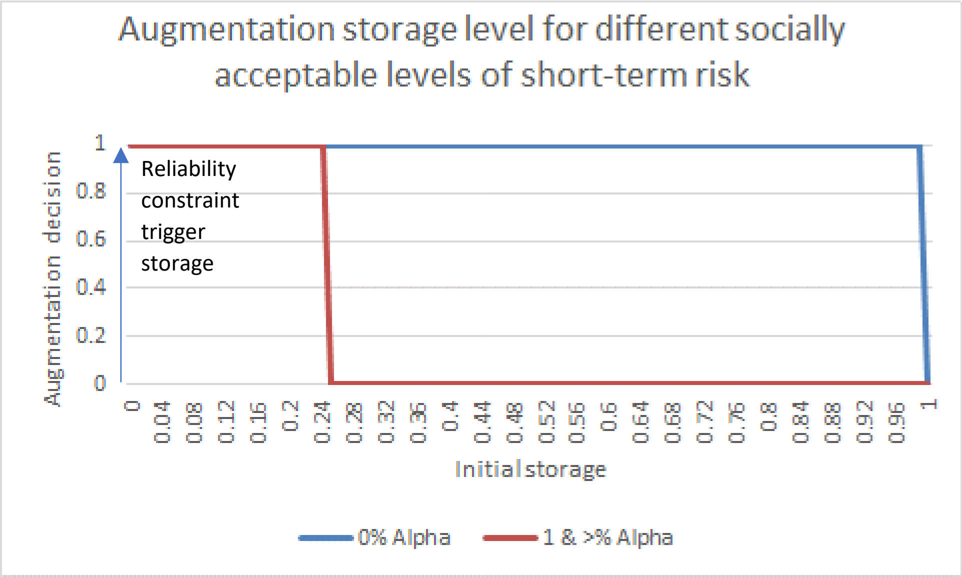

Figure 3-3: The augmentation triggers for different levels of socially acceptable short-term risk

Figure 3-3 shows whether the augmentation decision is made or not and the level of storages at which the short-term reliability constraint is not binding. The x-axis is the initial level of storage while the right is whether the augmentation has been triggered, set to one, or not, set to zero. The blue arrow, at 0.00 initial storages, is the point where the short-term reliability constraint is binding.

Figure 3-3 shows that when the socially acceptable level of short-term risk is zero, the level of storage at which the augmentation decision is triggered is 0.99. That is the risk constraint is determining the augmentation and it is only when the storage is initially completely full that the reservoir operator is able to determine whether to augment the water supply system or not. At all other storage levels, the reliability constraint forces the augmentation to take place, highlighting the cost of completely eliminating short-term risk from a water supply system. In contrast, when the socially acceptable level of short-term risk in one per cent or higher, the reliability constraint augmentation trigger is zero while the optimal point to augment the water supply system is initial storage level 0.24, implying that it is the cost minimisation that is determining the augmentation.

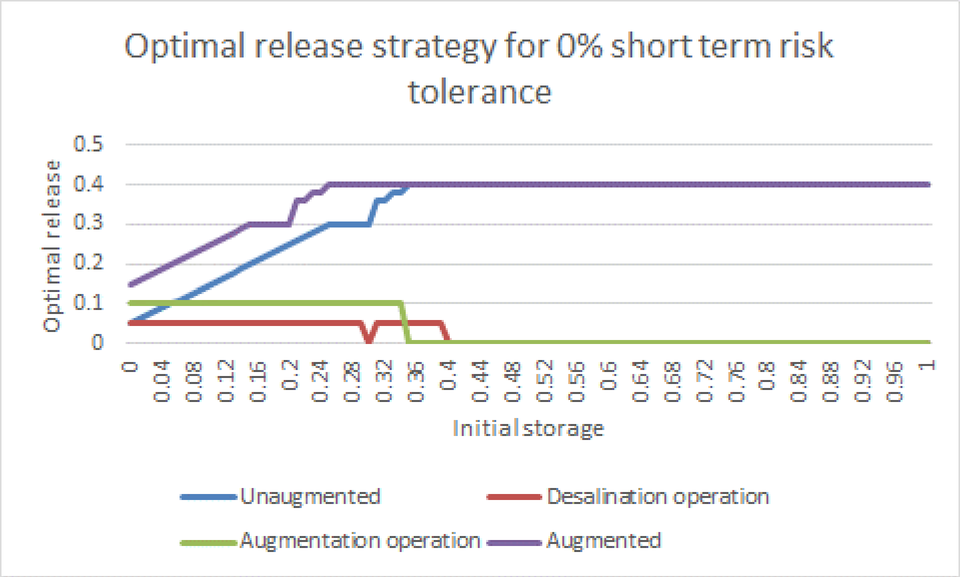

Figure 3-4: Optimal releases regimes for zero short-term risk tolerance, unaugmented and augmented states

Figure 3-4 shows the cost minimising optimal release strategy for the unaugmented and augmented water supply system as well as the range of initial storages the desalination plant is operated and those where the augmentation is operated. The x-axis is the initial storage, and the y-axis is the quantity of water to release or order from the desalination plant and augmentation. The optimal release strategy for the relatively low variance inflows of Model 6.1 (Relatively low variance) is static across all forty periods. However, there is a difference between the unaugmented system, which is represented by the first four periods, and the augmented system, which can occur when the augmentation is available to supply water.

When the socially acceptable level of short-term risk is zero per cent, then the optimal release in the unaugmented state is to operate the desalination plant and release all available water from initial storages 0.00 to 0.25. Between initial storages 0.25 and 0.29 the desalination plant continues to operate but not all available water released. This is because there isn't sufficient water available to go from the third to second level of restrictions. At initial storage level 0.30 the desalination plant is not operated. This is because it does not produce sufficient water to reach the second level of restrictions, the one above the minimum level of service or the third level of restrictions, and there is sufficient water available to meet the minimum service levels without the desalination plant operating. The desalination plant is then operated from initial storages 0.31 to 0.39 and is not used for the remaining storage levels. When initial storages are 0.31 the optimal release is 0.36, the second level of restrictions. This restriction level continues to initial storage level 0.32, whereupon the first level of restrictions are imposed from initial storages 0.33 and 0.34. When initial storages are 0.35 and higher the target demand is met for all storage levels.

In the augmented state, the optimal release strategy is to operate the desalination plant and augmentation option and release all available water from initial storages 0.00 to 0.14. The optimal release strategy involves operating the augmentation option at all storages where it is triggered, which is 0.24 and below. The desalination plant is operated at exactly the same range of storages as in the unaugmented state, with the exception of storage level 0.20, where it is not operated as there is sufficient water available with the augmentation to meet the minimum service level but not sufficient to reach level two restrictions. At storage level 0.15 to 0.20, the optimal release is to exactly meet the minimum service level. At storage levels 0.21 and 0.22 the second level of restrictions is imposed while the first level is imposed at storage levels 0.23 and 0.24. The target amount of water is then released for storage levels 0.25 to 1.00.

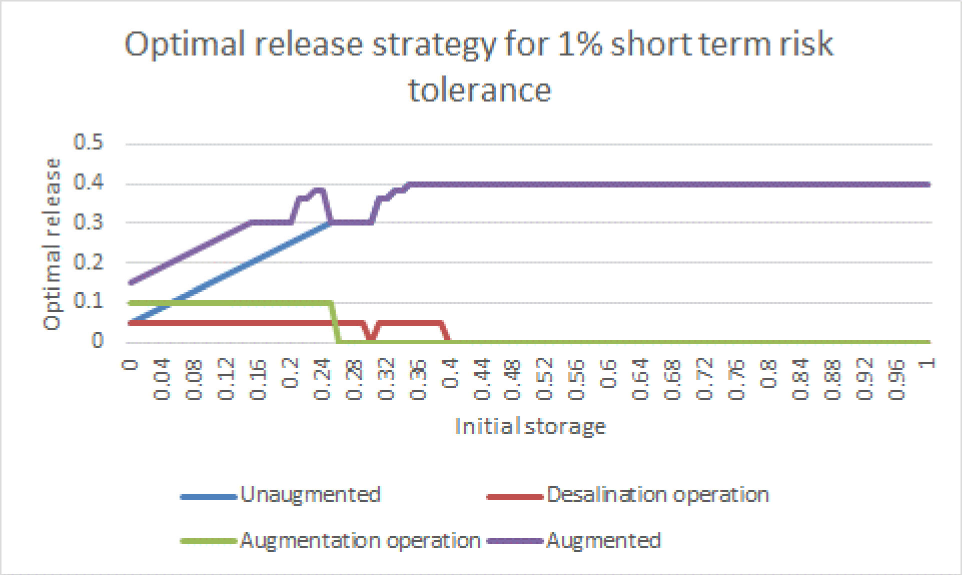

Figure 3-5: Optimal releases regimes for one per cent short-term risk tolerance, unaugmented and augmented states

Figure 3-5 is the same as Figure 3-4, but for a short-term socially acceptable level of risk of one per cent rather than zero per cent. The optimal release strategy for Model 6.1 (Relatively low variance), when the short-term risk tolerance is one per cent or higher is different depending on whether the system is augmented or not. For the first four periods, and for the four periods after the augmentation decision, the optimal release is static, but changes once the augmentation is available to produce water. The optimal release strategy in period one involves operating the desalination plant from storage level 0.00 through to 0.39, except at storage level 0.30 where there is sufficient water available to meet the minimum service level but not sufficient to meet the second level of restrictions, as it is when the socially acceptable short-term risk is zero per cent. The amount of water released is all available water until storage levels are at 0.25. Then from storge levels 0.25 to 0.30 inclusive the minimum service level is met, but no additional water is released. At storage levels 0.31 and 0.32 the second level of restrictions is imposed and then at storge levels 0.33 and 0.34 the first level of restrictions is imposed. At storage levels 0.35 and above the target demand is met but no additional water is released.

When the augmentation is available to produce water the optimal release changes. The optimal release involves operating the desalination plant from initial storages 0.00 to 0.39, with the only exceptions being at storage levels 0.20 and storage level 0.30. The additional augmentation is operated from storage level 0.00 through to 0.24. The optimal release involves distributing all water available from storage levels 0.00 to 0.15, then meeting the minimum service level from storage level 0.15 to 0.20. Storage levels 0.21 and 0.22 the restrictions regime level two is imposed, while restrictions level one is imposed at storage level 0.23 and 0.24. At storage level 0.25 through to 0.30, the optimal release falls back to meeting only the minimum level of storage as the augmentation option is not optimal to have built at this point. At storage levels 0.31 and 0.32 the optimal release is level two restrictions while at storage levels 0.33 and 0.34 the optimal release is restriction level one. At storage levels 0.35 and above the optimal release is to meet the target demand but not to exceed it.

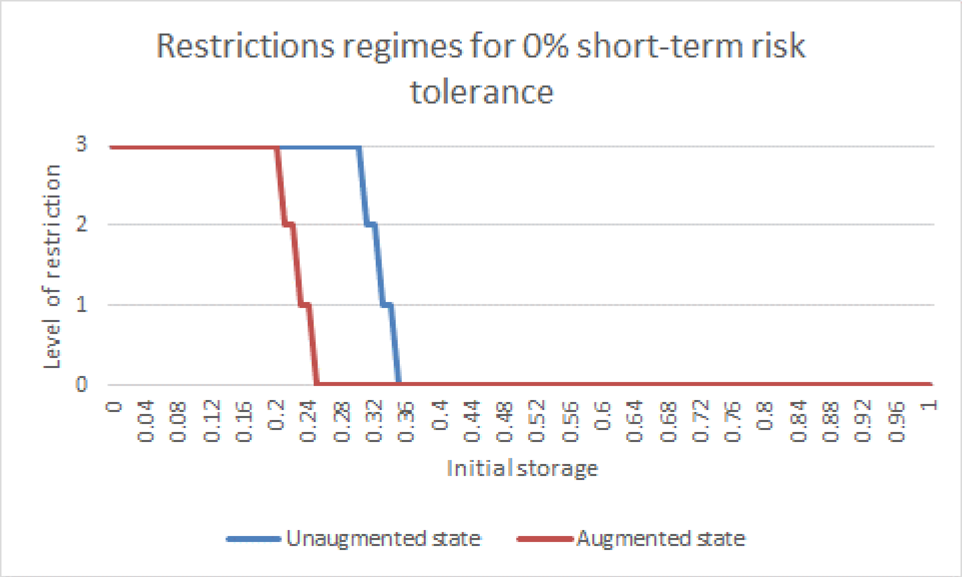

Figure 3-6: Restrictions regimes for zero short-term risk tolerance

Figure 3-6 shows the level of restriction imposed for a given level of storage for a zero per cent short-term risk tolerance. The x-axis is the level of storage while the y-axis is the level of restriction imposed. The target demand is represented by zero on the y-axis. The restrictions regime associated with the optimal release strategy when the short-term risk tolerance is zero is different in the unaugmented state and the augmented state. In period 1 it involves imposing the third level of restrictions from initial storage level 0.00 through to 0.30, then restrictions level two for storage level 0.31 and 0.32 and restrictions level one for storage levels 0.33 and 0.34. The target demand is met for all other storage levels. In period 5 the restrictions regime is to impose level three restrictions from storage level 0.00 through to 0.20, then level two restrictions for storage levels 0.21 and 0.22 with level one restrictions being imposed for storage levels 0.23 and 0.24. No restrictions are imposed from storage levels 0.25 and above.

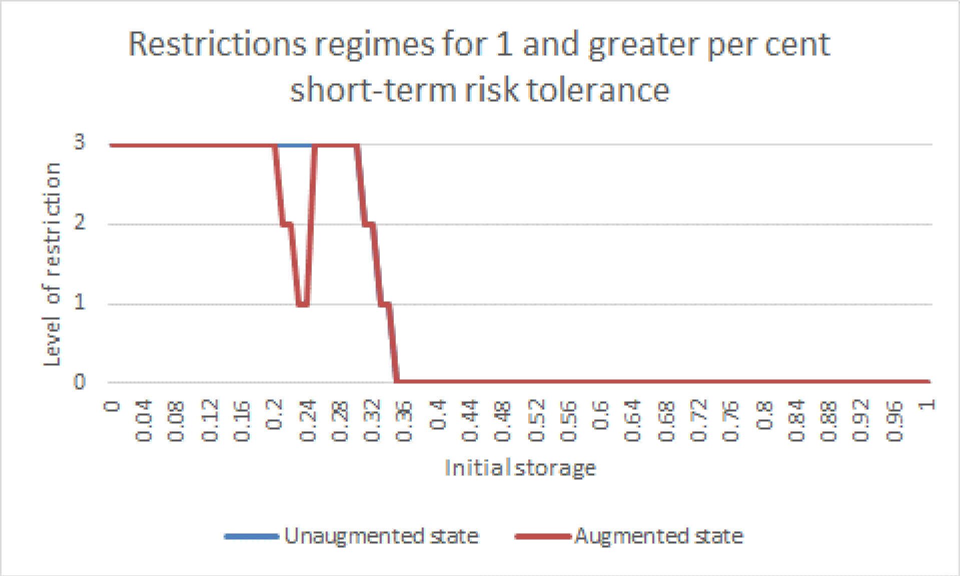

Figure 3-7: Restrictions regimes for one per cent short-term risk tolerance

Figure 3-7 is similar to Figure 3-6. The restrictions regime associated the short-term risk tolerance of one per cent or higher is the same in the unaugmented state as it is when the short-term risk preference is zero per cent. In the augmented state the restrictions regime is the same for storage levels 0.00 through to 0.29. At storage level 0.30, the restrictions regime falls back to being at level three, just meeting the minimum service level as the augmentation option is no longer operating, before returning to level two restrictions at storage levels 0.31 and 0.32 and level one restrictions at storage levels 0.33 and 0.34. No restrictions are imposed at storage levels 0.35 and higher in period 5.

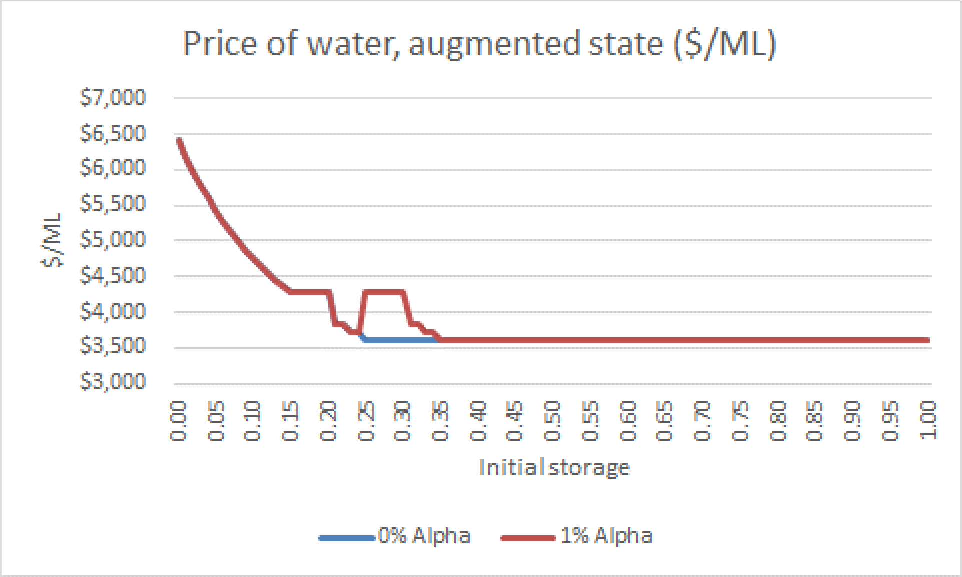

Figure 3-8: Price of water associated with Models 6.2, augmented state, with socially acceptable risk levels 0, and 1 per cent

Figure 3-8 shows the effective price of water given the level of restriction imposed by the optimal release strategy. Since the optimal release strategies are consistent in the unaugmented state, regardless of the socially acceptable short-term risk preferences, the effective price of water implicit in the quantity of water released does not vary. However, there is a different in the augmented state, reflecting how the augmentation operation decision varies based on short-term risk preferences. The scarcity price starts the same in both simulations, at $6,432 when storages levels are completely empty, and falls consistently until storages levels are at 0.24 and the implicit price of water is $3,717, At storage level 0.25 there is a slight difference in the price of water, with it falling to $3,606 when there is a zero short-term risk preference but rising to $4,273 when there is a one per cent or higher short-term risk preference. The prices in the two simulations continue to deviate over the storage levels 0.25 to 0.34, initially by $667 and then falling to $111 at storage levels 0.33 and 0.34, before the optimal release strategies become the same. When the target demand is met the implicit price of water is $3,606 which it is at over storage levels 0.25 to full for a zero short-term risk preference or from 0.35 to full for a one per cent or higher short-term risk preference.

The difference in augmentation triggers between a zero and one per cent or higher short-term risk preference results in different total expected costs over the planning timeframe. The total costs are described in the Figure 3-9.

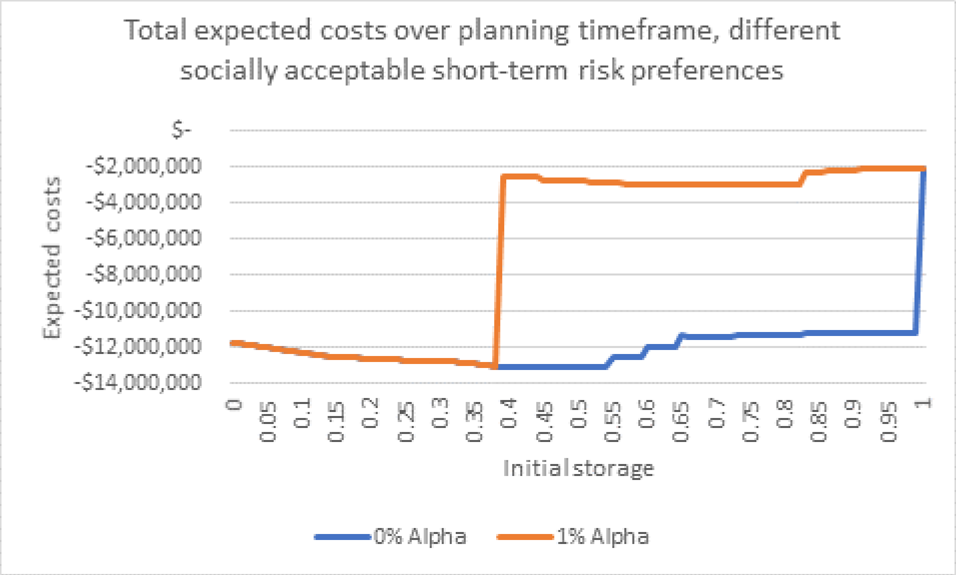

Figure 3-9: Total expected costs over the planning timeframe for the socially acceptable short-term risk of zero, one and two per cent

The total expected costs over the 40 periods of the model are a result of costs associated with delivering the water, operating the desalination plant, and capital and operation costs for the augmentation. The key factor leading to different costs with the two risk levels is the storage at which augmentation occurs. Both variations of Model 6.1 (Relatively low variance) have similar expected total costs between initial storages 0.00 to 0.38. The total expected costs both start at around $11,733,000 and slowly increase to around $13,063,000 in both simulations by initial storage level 0.38. At initial storage level 0.39 the zero short-term risk preference simulation total expected costs slowly increase, rising to $13,092,000 at initial storage level 0.51 and then declining consistently until initial storages reach 0.99, where the total expected costs are $11,149,000. When initial storages are completely full, the total expected costs fall significantly when short-term risk preferences are zero, to $2,134,000 as the augmentation option is not automatically triggered at this storage level.

When the short-term risk preference is one per cent or higher, the total expected costs drop significantly when the initial storages go from 0.38 to 0.39, as they change from $13,063,000 to $2,491,000. The total expected costs slowly increase to $3,016,000 at initial storage levels 0.70 to 0.74, before slowly falling as initial storages increase until they reach $2,134,000 at initial storage level 0.91 where they stay until storages are full.

The difference between the two different risk preferences described in Model 6.1 (Relatively low variance) with short-term risk preferences of zero per cent reflect additional costs associated with increased security for the water supply system and its ability to meet a minimum level of service. When the augmentation is triggered above the “optimal” initial storage for the cost minimisation model it generates additional costs. These costs come from the annual financial charge associated with the augmentation that are incurred irrespective of whether it is operated or not. The difference in total expected costs over the planning timeframe for different socially acceptable short-term risk preferences is described in the chart below.

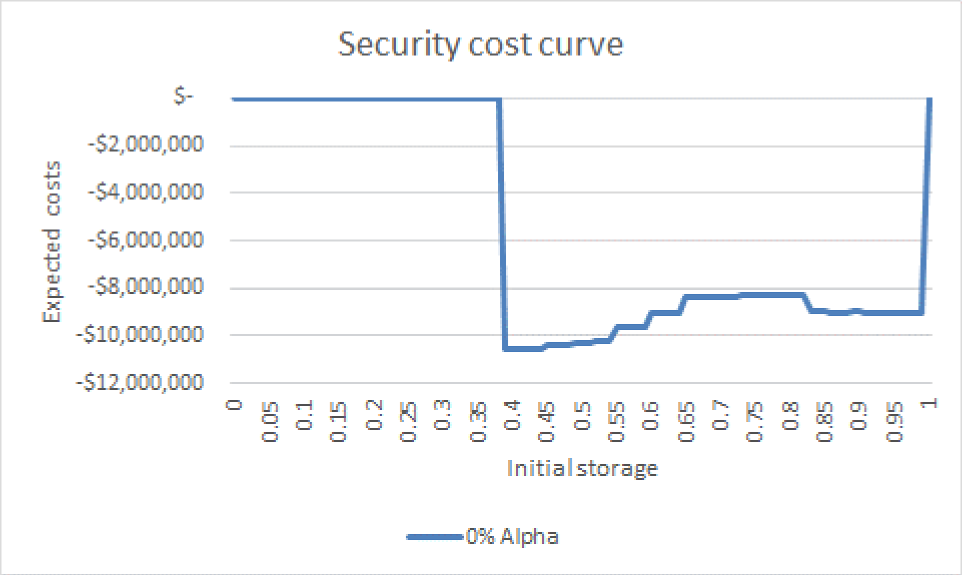

Figure 3-10: The security cost curve

Figure 3-10 shows the security cost curve for Model 6.1 Relatively low variance. It shows the additional costs that would be expected to be incurred for maintaining a zero per cent relative to a one per cent or higher short-term risk preference. When the socially acceptable level of short-term risk is zero, there are additional costs associated with having this level of security for all initial storages except when they are completely full. These additional costs start when the reliability constraint triggers an augmentation at a higher level than when the socially acceptable short-term risk preference is greater than zero. The additional costs are incurred when initial storages reach level 0.39 and they are $10,572,000 higher for having a lower short-term risk preference. The total additional security costs slowly decrease from initial storage level 0.39 to 0.80. From initial storage levels 0.81 to 0.88 the total expected cost of maintaining the water supply system slightly increases, rising from -$8,299,000 to -$9,015,000 before falling slightly over initial storage levels 0.89 and 0.90 when they are -$8,932,000. Over initial storge levels the additional costs associated with maintaining a water supply system with zero short-term risk, as defined in Model 6.1, is $9,015,000 more than at a higher level of short-term risk tolerance. When initial storages are completely full there is no additional expected total costs associated with different short-term risk preferences.

6.4.2 Model 6.2 (Relatively high variance)

This model is the same as Model 6.1 (Relatively low variance), but the inflows have higher variance. Consequentially the reliability constraint is binding at or above the level of storage for the same socially acceptable short-term risk in Model 6.1. A higher variance of inflows means that the short-term risk constraint is binding for a wider range of initial storages and will result in a higher total expected cost of maintaining the water supply system. Comparing Models 6.1 and 6.2 highlights the additional costs associated with mitigating short-term risks due to greater variability in inflows.

The following socially acceptable levels of short-term risk were examined, 0%, 1%, and 2%. The optimisation results show that the reliability constraint is not binding at acceptable short-term risk levels of 2 per cent or higher. The level of initial storage at which the reliability constraint is binding, S_{aug}, is described in the figure below.

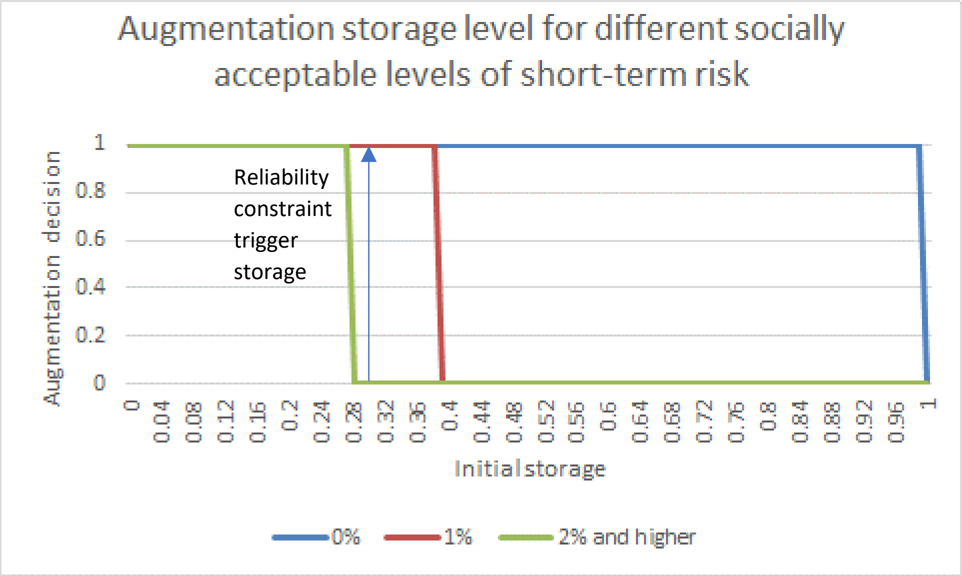

Figure 3-11: The augmentation triggers for different levels of socially acceptable short-term risk

Similar to Figure 3-3, Figure 3-11 shows whether the augmentation decision is made or not and the level of storages at which the short-term reliability constraint is not binding. The x-axis is the initial level of storage while the right is whether the augmentation has been triggered, set to one, or not, set to zero. The blue arrow, at initial storage level 29 per cent, is the point where the short-term reliability constraint is binding. When the socially acceptable level of short-term risk is zero, meaning that there needs to be sufficient water in storage to meet the minimum service level over the augmentation timeframe, the level of storage at which the augmentation decision is triggered is 0.99. That means that only when the initial storages are completely full is the reservoir operator able to determine whether to augment the water supply system or not. At all other storage levels, the reliability constraint forces the augmentation to take place.

As the level of acceptable short-term risk increases the augmentation trigger level of the reliability constraint falls. When the socially acceptable level of short-term risk is 1 per cent, the augmentation trigger falls from 0.99 to 0.38. At 2 per cent acceptable short-term risk the augmentation trigger is at 0.27 of initial storages. This is below the optimal release strategy augmentation trigger of 0.31, meaning the reliability constraint is not binding on the decision of the reservoir operator to augment or not to augment. At higher levels of acceptable short-term risk the reliability constraint is irrelevant to the outcomes of Model 6.2 (Relatively high variance) as it is not binding.

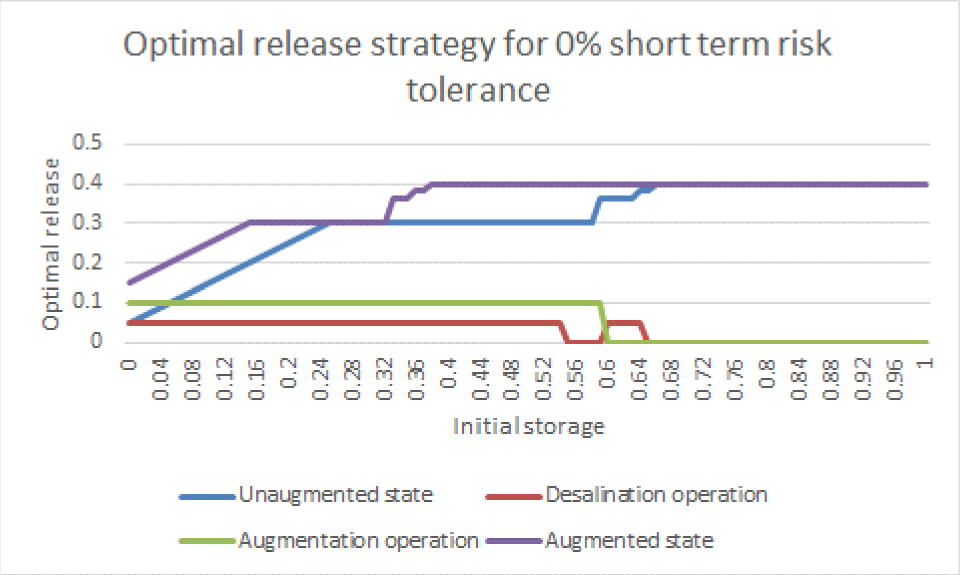

Figure 3-12: Optimal releases regimes for zero short-term risk tolerance, unaugmented and augmented states

Figure 3-12 shows the cost minimising optimal release strategy for the unaugmented and augmented water supply system as well as the range of initial storages the desalination plant is operated and those where the augmentation is operated. The x-axis is the initial storage, and the y-axis is the quantity of water to release or order from the desalination plant and augmentation. The optimal release strategy when short-term risk preferences are zero varies over the augmentation timeframe before stabilising when it has been constructed. In the first period, the unaugmented state, the optimal release involves operating the desalination plant from initial storages 0.00 to 0.88. While the amount of water released starts at 0.05 at initial storage 0.00, rising to 0.30 by initial storage 0.25. The optimal release stays at 0.30 between initial storage 0.25 to 0.57, and then rises to 0.36, which is the release for the second level of restrictions, for initial storages 0.58 to 0.63. The first level of restrictions, resulting in releases of 0.38, occur over initial storages 0.64 and 0.65. Thereafter the cost minimising optimal release is the target demand over initial storages 0.66 to 1.00.

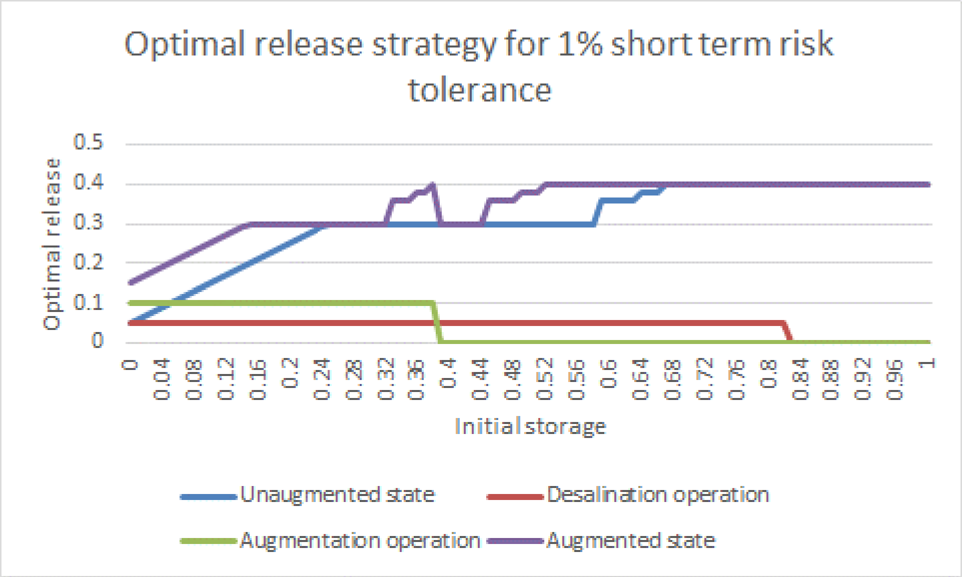

Figure 3-13: Optimal releases regimes for one per cent short-term risk tolerance, unaugmented and augmented states

Figure 3-13 is similar to Figure 3-12 except it describes the optimal release strategy when the short-term socially acceptable risk preference is one per cent rather than zero. When the short-term risk preferences are one per cent, then the augmentation trigger drops to 0.38. Consequentially, considering the augmentation is constructed and the capital costs are fixed, the optimal release involves it operating until initial storages are 0.38. The desalination plant is optimal to operate until initial storages are at 0.82.

The optimal release strategy in period one involves releasing the maximum amount possible for initial storages 0.00 to 0.25, from initial storages 0.25 to 0.58 the third level of restrictions is imposed. Then, from initial storages 0.59 to 0.63 the second level of the restriction regime is imposed while from 0.64 to 0.66 the first level of restrictions is imposed. From initial storages 0.67 and above the target demand is met.

The optimal release strategy in the augmented state, available from period five onwards, is more complex as this is when the augmentation option has been constructed. Between initial storages 0.00 and 0.14, the maximum amount of water available is released. From storages 0.15 to 0.32 the third level of restrictions are imposed, and then again at storages 0.39 to 0.44. The gap is due to the availability of the augmentation option, due to the reliability constraint. The second level of restrictions is imposed from storages 0.33 to 0.35 and then from 0.45 to 0.48. The third level of restrictions is imposed from 0.36 to 0.37 and then from 0.49 to 0.51. The target demand is met at storage levels 0.38 and then at 0.52 through to 1.00. The range at which the target demand can be met is much larger when the augmentation option is available.

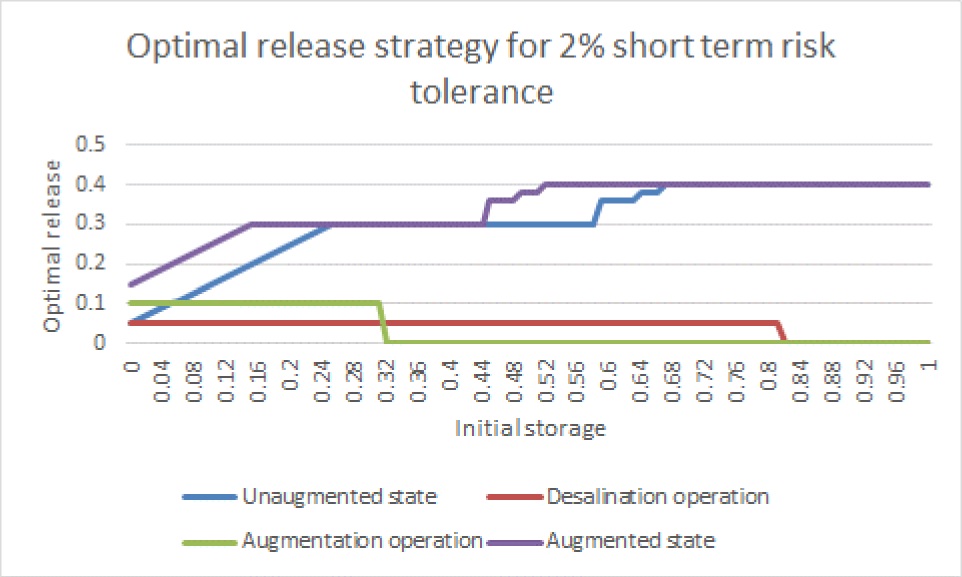

Figure 3-14: Optimal releases regimes for two per cent and higher short-term risk tolerance, unaugmented and augmented states

Figure 3-14 is similar to Figure 3-12 except it describes the optimal release strategy when the short-term socially acceptable risk preference is two per cent rather than zero. When the short-term risk preferences are two per cent or higher the reliability constraint is not binding and it is optimal for the reservoir operator to augment the water supply system at initial storages of 0.31. The optimal release involves operating the augmentation from storage level 0.00 to 0.31. The desalination plant is operated from initial storages 0.00 to 0.90 in period one but only from storage levels 0.00 to 0.82 when the augmentation option has been constructed in period five.

The optimal regime in the unaugmented state involves imposing level three restrictions from initial storages 0.00 to 0.58. Then the second level of restrictions are imposed from initial storages 0.59 to 0.63. The first level of restrictions is imposed from initial storages 0.64 to 0.66 while the target demand is met for all initial storages at or above 0.67. In the augmented state, the augmentation option is operational. Consequentially, the third level of restrictions is imposed over storage levels 0.00 to 0.44. The second level of restrictions is imposed over storage levels 0.45 to 0.48. The first level of restrictions is imposed over storge levels 0.49 to 0.51. The target demand is met for all storage levels above 0.51.

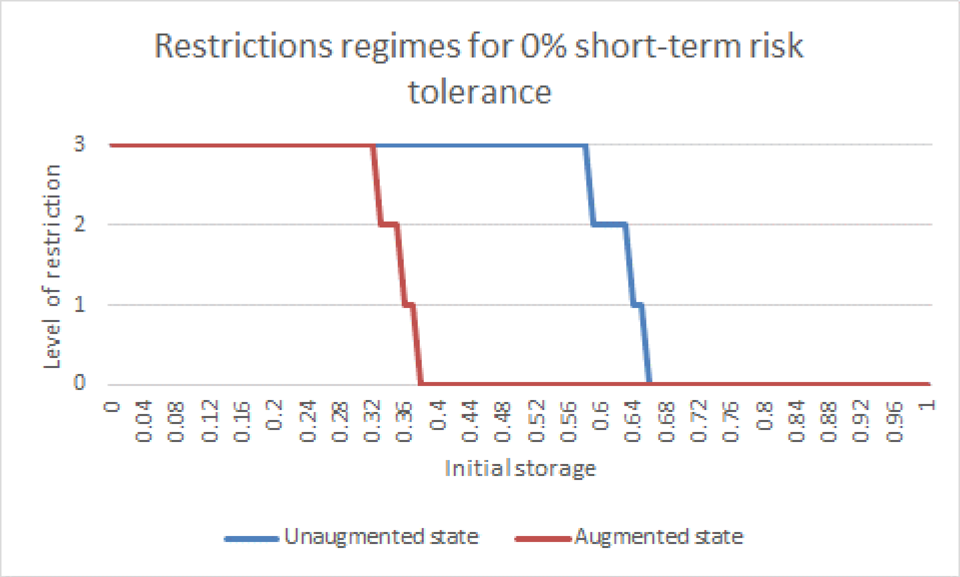

Figure 3-15: Restrictions regimes for zero short-term risk tolerance

Figure 3-15 shows the level of restriction imposed for a given level of storage for a zero per cent short-term risk tolerance. The x-axis is the level of storage while the y-axis is the level of restriction imposed. The target demand is represented by zero on the y-axis. When the socially acceptable level of short-term risk is zero, and the augmentation trigger occurs at initial storage level 0.99, the optimal restriction level to impose is the highest level of restrictions from initial storage level 0.00 through to 0.58 inclusively. Then the second level of restrictions is imposed from initial storage level 0.59 to 0.63, while the lightest level of restriction is imposed from initial storages 0.64 to 0.66. At initial storages 0.67 and higher the target demand is always met. In period five, when the decision to augment the water supply system means that additional supply is available, the restrictions regime is to impose level three restrictions from initial storages 0.00 to 0.44. The reduction in initial storages at which level three restrictions are imposed is greater than the capacity of the augmentation option. This suggests the augmentation option provides security benefits greater than its capacity to produce water for consumption. The second level of restrictions is imposed over a slightly smaller range of initial storages compared to the unaugmented state, from 0.45 to 0.48. Likewise, the first level of restrictions is also imposed over a smaller range of initial storages, 0.49 to 0.51.

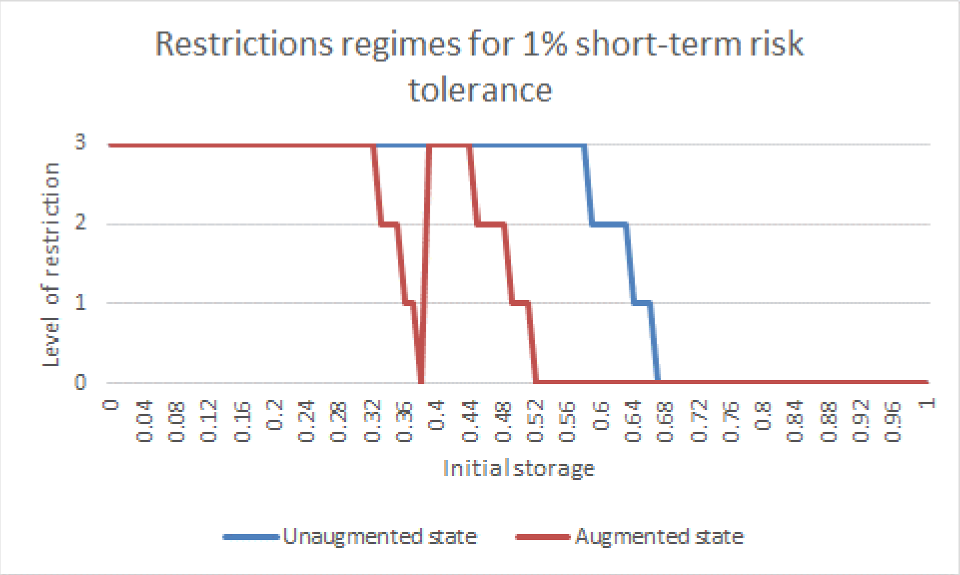

Figure 3-16: Restrictions regimes for one per cent short-term risk tolerance

Figure 3-16 is similar to Figure 3-15, except it describes a one per cent short-term risk tolerance. When the socially acceptable level of short-term risk is one per cent the optimal release restrictions regime is a little more complex. The restrictions regime in the unaugmented state is the same as for when the short-term risk is zero with the exception that the first level of restrictions is applied from initial storages 0.63 to 0.66 rather than 0.63 to 0.65. The difference is because the augmentation has already been triggered when short-term risk preferences are zero while they have not when short-term risk preferences are one per cent. The complexity occurs in the augmented state where level three restrictions are imposed between initial storages 0.00 to 0.32 and then again between 0.39 to 0.44. Likewise, level two restrictions are imposed between initial storages 0.33 and 0.35 then again between 0.45 and 0.48. While level one restrictions are imposed between initial storages 0.36 to 0.37 and then 0.49 to 0.51. The reason for the gap is due to the reliability constraint forcing the reservoir operator to augment the water supply system up to initial storage level 0.38, which means that at that level of initial storage, when the desalination plant and augmentation option both operate there is sufficient water to meet the target demand. However, as its optimal to impose restrictions but not augment above that level of storage, it is better to impose restrictions when initial storages are above the reliability constraint-imposed augmentation trigger.

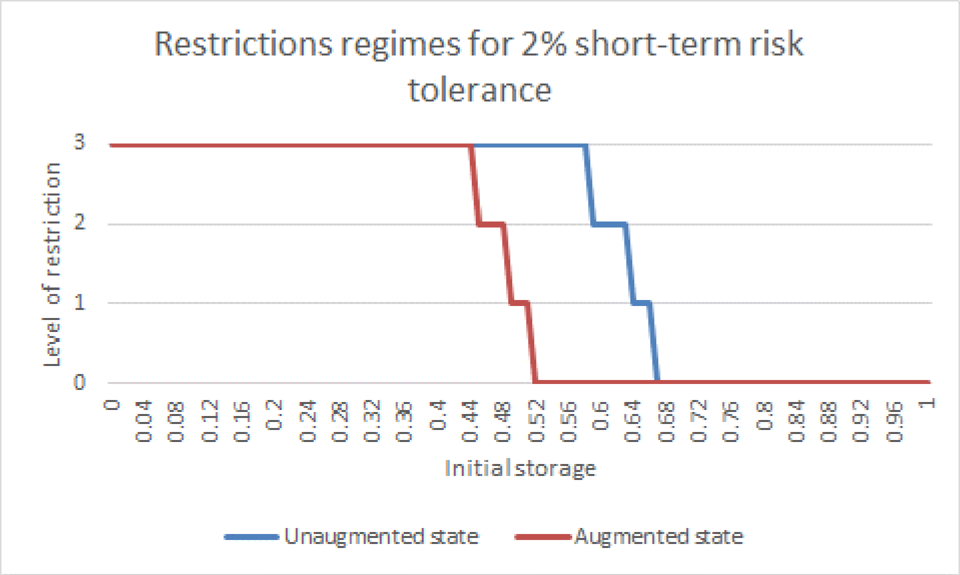

Figure 3-17: Restrictions regimes for two per cent and higher short-term risk tolerance

Figure 3-17 is similar to Figure 3-15, except it describes a two per cent short-term risk tolerance. The restrictions regime for short-term risk preferences of two per cent or higher are more straightforward given the reliability constraint is not binding. The optimal release involves augmenting the water supply system before the reliability constraint is met. In the unaugmented state restrictions regime is exactly the same as the period one restrictions regime when short-term risk preferences are one per cent. In period five, third level restrictions are imposed between initial storage 0.00 to 0.44, then second level between 0.45 to 0.48 and the first level of restrictions between storages 0.49 to 0.51.

The largest differences in the optimal release strategies occur when the augmentation option becomes available for use. Consequentially, this chapter describes the implied shadow price of water in period five when the augmented state of the water supply system is available for comparison for short-term risk preferences zero, one and two per cent.

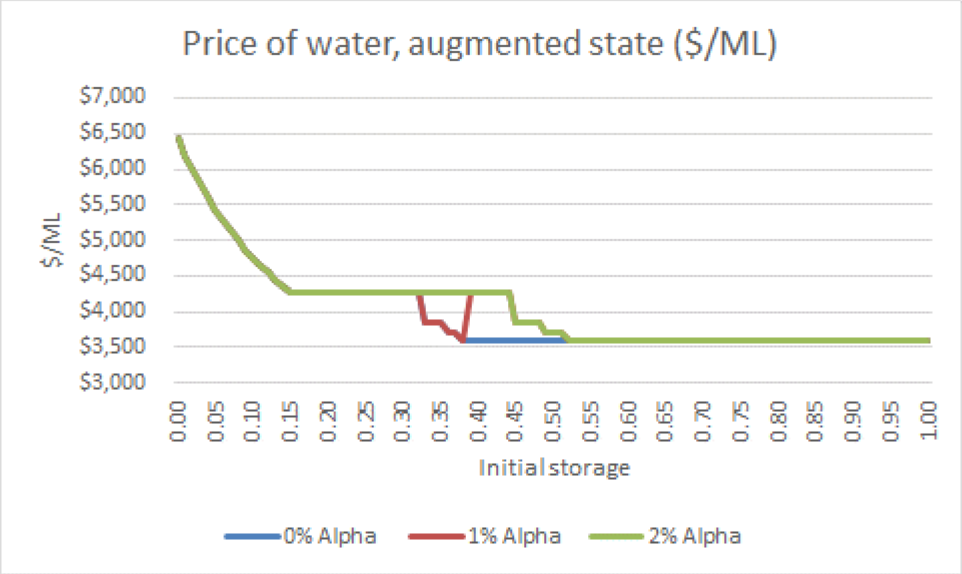

Figure 3-18: Shadow price associated with Models 6.2, augmented state, with socially acceptable risk levels 0, 1 and 2 per cent

Figure 3-18 shows the effective price of water given the level of restriction imposed by the optimal release strategy. The effective price associated with the optimal release function is similar for all variants of Model

6.2 (Relatively high variance). The price starts high when there is little water available, just that produced by the pre-existing desalination plant and the augmentation option, when storages are 0.00 and the corresponding price of water is $6,432 per megalitre. The price falls consistently as the amount of water available increases until storage level 0.15 where it is at $4,273 and remains at this price for all three variants until storages reach 0.32. Above this, the price of water varies based on the influence of the reliability constraint.

When the socially acceptable level of short-term risk is zero, the price of water above storages 0.32 to 0.35 falls to $3,837 as the second level of restrictions are imposed. From storage levels 0.36 to 0.37 the first level of restrictions are imposed, and the price of water is $3,717, before the target demand is met at storage levels 0.38 and above, resulting in a price of water of $3,606.

When the socially acceptable level of short-term risk is two per cent, or higher, the price of water related to the optimal release strategy remains at $4,273 until storages are at 0.44, reflecting the level three restrictions. From storages 0.45 to 0.48 the price of water is $3,837 reflecting the value of water when the second level of restrictions and from 0.49 to 0.51 the price is $3,714 as the first level of restrictions is imposed. For storages 0.52 to 1.00 the target amount of water is released, resulting in the price of water being $3,606 based on the demand for water curve used in the model.

The total cost of maintaining the water supply system is influenced by the socially acceptable level of short-term risk and the corresponding augmentation trigger. This is described in the chart below.

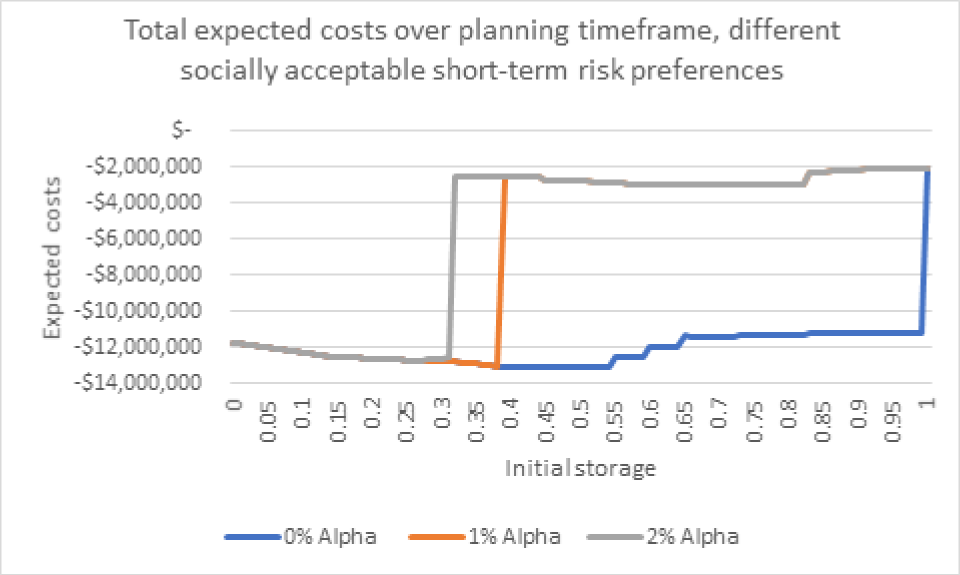

Figure 3-19: Total expected costs over the planning timeframe for the socially acceptable short-term risk of zero, one and two per cent

The total expected costs over the 40 periods of the model are a result of costs associated with delivering the water, operating the desalination plant, and capital and operation costs for the augmentation. All three variations of Model 6.2 (Relatively high variance) have similar expected total costs between initial storages 0.00 to 0.28. The costs associated with having a short-term risk preference of two per cent or higher go from $12,549,000 to $240,000 at initial storages 0.31 to 0.32. As the initial storage level increases the expected costs increase from level 0.32 to 0.69. Thereafter the total expected cost starts to decline, reaching $2,134,000 at initial storage level 0.91. The total expected costs remain at this level for the initial storages 0.91 to 1.00.

The difference between the variants of Model 6.2 (Relatively high variance) with short-term risk preferences below two per cent reflect additional costs associated with ensuring a more secure water supply system. These costs come from the annual financial charge associated with the augmentation that are incurred irrespective of whether it is operated or not.

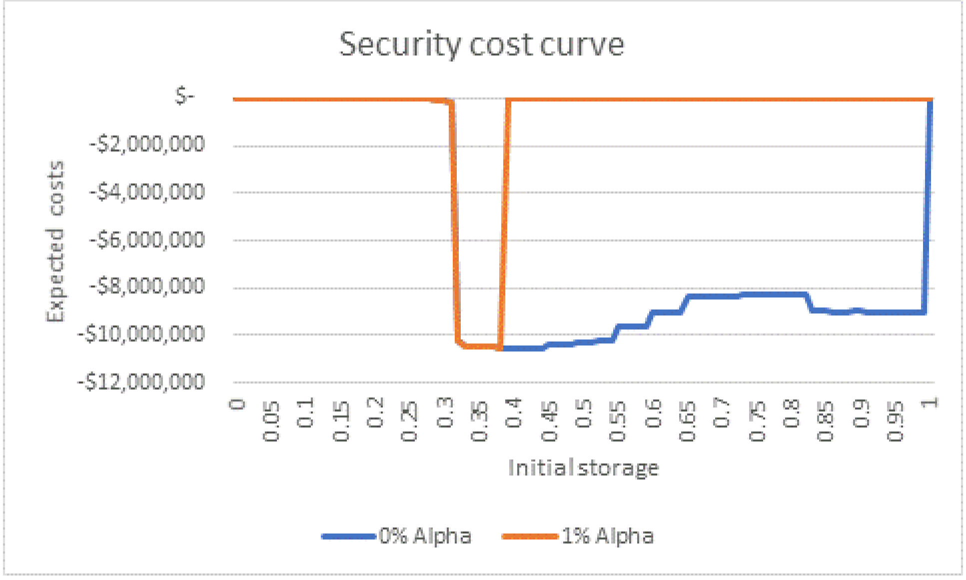

Figure 3-20: The security cost curve

When the socially acceptable level of short-term risk is zero, there are additional costs associated with having this level of security for all initial storages except when they are completely full. The additional costs start above the storage level it is optimal to augment the water supply system at, initial storages of 0.27, and continue until storages are 0.99. They start at a relatively small amount, an expected additional $35,362 in costs over the timeframe, when initial storages are 0.28 but rise to $10,217,000 when initial storages are 0.32 due to the total expected capital and operating costs associated with the augmentation option. The additional costs stay above $10 million until the initial storage reaches 0.54, where they then drop to $9,634,000. The additional security costs continue to decline until they reach $8,296,000 at initial storage level 0.80 whereafter they start increasing back to $9,015,000 at initial storage level 0.86. The additional costs stay around $9,015,000 until storages reach 0.99 when they drop to zero at full storages.

When the socially acceptable level of short-term risk is one per cent, the additional security costs are considerably less than when it is zero. The additional costs are incurred when initial storages are 0.28, an expected additional $35,362 in costs over the model's time horizon. They slowly increase to $157,790 at initial storage level 0.31 and then jump to $10,217,000 at initial storage 0.32. The security costs stay around this amount until the initial storage reaches 0.39, where they drop to zero. At initial storages 0.39 and above the costs of maintaining the water supply system are the same as when the short-term risk is two per cent or higher.

6.5 Discussion

This chapter examines the optimal release when the reservoir operator is not able to apply perfectly adjustable prices. The cost minimising model used in this chapter highlights the influence short-term risk tolerance has for the decision to augment the water supply system. It also shows that the optimal release will be significantly different based on the level of short-term risk that is accepted. Eliminating short-term risk carries relatively large costs compare with accepting a level of risk that the minimum level of service cannot be met. The expected variance in inflows also has a significant influence on the operation of a water supply system. With higher variance in inflows requiring more insurance in terms of water held in storage and also augmentation decisions occurring at a higher level of service.

The model incorporates uncertain inflows and determines the optimal quantity of water to release at each of 101 initial storage increments through the use of the Bellman Equation to solve a 40-year planning period recursively. Unlike the models in Chapter 5, the models in this chapter have four discrete quantities of water to release: the target amount, two specific levels of restricted demand, and the minimum level of service (level three restriction), or as much of it as can be met. Risk preferences are incorporated into the model in three ways. The first is in the assumed constant absolute risk aversion of the demand response to changes in available resource, and hence the trade-off between consumption today and consumption tomorrow. The second is the inclusion of a minimum level of service that has a loss function associated with not meeting it while the third is through a short-term risk constraint that prompts an augmentation of the water supply system. The reservoir operator has three decisions, what quantity of water to release, whether to operator the pre-existing desalination plant or not, and whether to augment the water supply system or not.

The optimal release can be established for a water supply system with a climate independent augmentation option available and a pre-existing desalination plant. This optimal release establishes the restrictions regime, and the resultant quantities of water to be released in each period and is influenced by the level of short-term risk preference. Having an augmentation option available changes the optimal release function as it results in a different amount of water being released, for a range of initial storages, when the augmentation has been constructed and is available to produce water. The difference in the optimal release is that over the range of initial storages 0.00 to 0.15, the operation of the augmentation means that 0.10 additional units of water are available. Between initial storages 0.16 and 0.20, the difference between period 1 and 5 falls by 0.01 each storage increment before rising back to 0.10 at initial storage 0.21. Between initial storages 0.21 and 0.30 the difference between the two periods varies between 0.10 and 0.09. For storage increments 0.31 and 0.32 the optimal release is 0.04 higher in period 5, while for storage increments 0.33 and 0.34 it is 0.02 higher in that period. This reflects the greater level of water availability due to the augmentation option having been triggered.

The operation of the desalination plant is not influenced by the augmentation option. It is optimal to operate it for all initial storage levels between 0.00 and 0.39 except for initial storage level 0.30. This is because the restrictions regime allows for the release of the minimum service level, but the next level of restrictions is 0.06 higher and so operating the desalination plant does not provide sufficient water to meet this quantity. The only change is when the augmentation option is triggered and has been built, then the desalination plant is not operated at storage increment 0.20 as well, as the augmentation option can produce enough water to meet the minimum service level but there is not the capacity to produce enough water to meet the next level of the restrictions regime.

The short-term socially acceptable level of risk has implications for both the augmentation decision as well as the optimal release function and also the augmentation decision. The only level of short-term risk that the reliability constraint was binding in Model 6.1 is when sufficient water had to be held in storage to meet the minimum service level over the augmentation timeframe. This results in the reliability constraint being binding at the initial storage level 0.99 and under. Consequentially the augmentation option is triggered for all initial storage levels except when storages are completely full. In contrast, when the short-term risk preference allows for inflows to be at the one per cent or higher to be included in the reliability constraint, then the reliability constraint is not binding and the augmentation is triggered at a level that is optimal according to the Bellman Equation.

The level of socially acceptable short-term risk has an influence on the operation of the augmentation and the optimal release. Over the range of storage levels 0.25 and 0.34 more water is released when short-term risk preferences are zero compared to when they are one per cent of inflows or higher. However, the total expected cost of operating the water supply system is also higher for all storage levels from 0.25 through to 0.99. The additional costs associated with having a lower risk preference can be considered the security cost for the water supply system. Across all initial storages the additional expected total costs can be considered the security cost function.

The influence of short-term risk preferences on the optimal release function and augmentation decision is significant. While water supply systems are regulated, and their risks understood, in the long-term, the trade-offs resulting from short-term risks is not incorporated into the way that water supply systems are regulated. This is despite the significant additional costs associated with having water security.

When the level of variance in inflows is increased, in Model 6.2, the optimal release, desalination plant operation rules, augmentation decision and security cost function all change. With higher variance inflows, the reliability constraint is binding at short-term risk preferences zero and one per cent while not being binding at 2 per cent or higher, influencing the optimal release function.

The optimal release function for Model 6.2, when short-term risk preferences are zero, results in more water held in storage than in Model 6.1. In period 1, more water is held in storage in model 6.2 over initial storage increments 0.31 to 0.65. Whereas in period 5 the amount of water held for future consumption is higher at storage increments 0.21 through to 0.37. Over these storage levels there is less consumption of water today due to a higher risk that the minimum storage level will not be met in the future.

The range over which the desalination plant is operated changes significantly in Model 6.2 such that, in period 1 it operates over the initial storage range of 0.00 through to 0.88. However, by period 5 the desalination plant operates over the storage range of 0.00 to 0.64, with the exception of storage levels 0.55 to 0.59. This also reflects the higher value associated with securing future consumption. Likewise, the range over which the augmentation option operates is also greater, being from 0.00 to 0.59 in Model 6.2.

As the socially acceptable level of short-term risk increases the optimal release changes. In period 1 the only storage increment that is different is that at 0.66 where 0.02 units of additional water are released when the socially acceptable level of risk is zero compared to when it is one. However, by period 5, and all subsequent periods in the model, the range of storage increments that release more water has expanded to be between 0.39 to 0.51. The additional water released starts at 0.10 for storage levels 0.39 to 0.44 and then falls to 0.04 and then 0.02, reflecting changes in the restriction regime due to short-term risk preferences.

When the short-term risk preference is two per cent or higher, the optimal release is changed. While period 1 has the same difference as zero and one per cent short-term risk preferences do for Model 6.2, in period 5 the range of storage increments over which more water is released is from 0.33 to 0.51. This additional water represents a range where level 2 and level 1 restrictions are imposed, when the short-term risk preference is zero, but restriction level 3 is imposed when the short-term risk preference is two per cent or higher. Then the target demand is met, from storage levels 0.38 to 0.44, before imposing restriction levels 2 and 1 earlier than when short-term risk preferences are two per cent or higher.

The reliability constraint is binding at the same initial storage increment as in Model 6.1, at 0.99 when the short-term risk preferences are zero. However, when they are one per cent the reliability constraint is binding at initial storage 0.38 in Model 6.2 while it is not binding in Model 6.1 at this short-term risk preference.

Different levels of short-term risk preferences result in different levels of expected total costs associated with maintaining the water supply system. This can be seen in the total expected costs being higher for initial storage levels 0.39 to 0.99 and 0.28 to 0.99 for zero compared to one and two respectively short-term risk preferences. The additional costs represent a security cost function for reducing the probability that the water supply system will not meet the minimum service level.

It should be noted that the security cost function is not incorporated in the currently regulatory framework for water supply systems. Nor does it influence the optimal release function in the benefit maximising model. This means that the costs associated with the security cost function are not explicitly incorporated into the drought response planning of water utilities. Likewise, it means that trade-offs involved are not objectively considered when setting the drought response plan.

It is important to note that, just as the benefit maximising model presented in Chapter 5 relies on a number of assumptions that are difficult to validate, so to does the cost-minimising model presented in this chapter. For instance, that demand is accurately forecast and reflective of consumer preferences and that reliability preferences are also represented.

6.6 Conclusion

Short-term risk preferences influence the cost of managing a water supply system. These costs can be significant. Moving from a two-percent risk of not having enough water to meet the minimum standard of service to one percent change creates additional costs. Eliminating the risk creates even more. The higher the level of variance in expected inflows the higher the security cost function will be, relative to low variance inflows. The security cost function describes the additional expected total costs of maintaining a given level of short-term risk. It is noteworthy that current regulatory regimes do not incorporate short-term risk preferences, despite the potential to have significant implications for the cost of operating the water supply system. In addition, existing drought response plans have an implicit level of short-term risk preference that has not been quantified, meaning the trade-offs involved in increasing the level of security in the water supply system will not have been defined.