THE COST OF RELIABILITY

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ABSTRACT

The uncertainty of rainfall is a key characteristic of water supply systems and creates a trade off between risk of running out of water and the infrastructure that underpins its supply. The advent of economically feasible, although expensive, manufactured water, such as desalination plants or recycled water, creates a potential upper bound on the social losses associated with reservoir failure. As such, it can be used to determine the cost of reliability standards. This paper examines how the amount of water demanded as a portion of average stream inflow, the acceptable probability of failure, and the augmentation timeframe influence the cost of reliability. In so doing it sets out a methodology for costing the reliability requirements in service level obligations and to interpret hydrological risk on an economic basis.

INTRODUCTION

The defining characteristic of the urban water sector is the uncertainty associated with rainfails. Unfortunately this creates a trade-off between the cost for supplying water and its reliability, particularly in Australia. The cost of having water available when customers want it means building dams, desalination plants, recycling facilities and the range of bulk headworks that supply Australia's urban centres.

Regulators and utilities are well aware of this trade off between reliability and the investment in infrastructure which underpins it. It is built into the restrictions regime and the service level obligations that utilities are required to work towards (Dept of Energy Supply, 2013). However, these restrictions regimes and regulatory frameworks are based on steady state estimates of water supply reliability, not explicitly consumer preferences. A major reason for not providing more consumer choice relates to the consequence of catastrophic reservoir failure and uncertainty about its riskiness.

Reservoir decision making has historically been made to try and minimise expected losses, sacrificing more frequent losses of relatively low value water to try and ensure the capacity to deliver high value water in the future. However, having the ability to produce water, albeit expensively and with a lag, creates an upper bound on the social losses associated with reservoir failure. It also creates a new opportunity cost associated with water in storage and its contribution to avoiding early or unnecessary augmentations.

Despite the complexities involved, the decisions of a reservoir operator have been frequently conceptualized as a simple two-stage model: either releasing stored water from a reservoir for beneficial use in the current period or retaining water for future use. The problem of how much water to withhold from immediately beneficial deliveries, retaining that water in storage, is known as ''hedging'' (Bower et al. 1962). Historically, hedges that underpin restrictions regimes have been developed based on the trade-offs between constraining current demand and ensuring future, high value, demand can be met. Given the loss of water in storage due to evaporation and seepage, and are subject to greater uncertainty given variable hydrological inflows, and the time value of money, the presumed future demand met by water in storage must be of greater value than the demand that is not being met at the moment. This is why it is phrased as meeting 'catastrophic' future reservoir failure.

Typical analysis of the reservoir operation decision is described in Figure 1. This outlines the decision of a reservoir operator as either to release all water available (described as the Standard Operating Policy (SOP) developed by Maass et al. 1962 and Loucks et al. 1981), or to restrict the amount of water released and hold some water in storage to hedge against future, more substantive, losses. In the diagram, feasible releases are constrained between the two blue parallel lines. The black line represents the release of all water available, with none left in storage, until the target demand is met, at which point water is held until storages are full, after which water starts to spill. In essence, SOP places the highest priority on releasing water for immediate beneficial use, up to the level of target demand, after which remaining water available is stored until storage capacity is reached. The feasible release zone is constrained by the left parallel line, which is releasing all water available, and the right parallel line, where is to fill storages and then release all available water.

Hedging, described by the dark line in figure one, involves constraining current demand to forestall catastrophic failure of future demand, was first introduced for rational operation according to time preference of water storage in the field of national resources economics. Masse (1946) analysed reservoir operation problems using the economic concept of marginal value. Then Gessford and Karlin (1958) presented a general mathematical analysis for optimal reservoir release policy and discussed the conditions of the existence of an optimal policy.

Draper and Lund (2004) translated hedging from gross loss to net benefit by replacing supply deficit with water use benefit. On this basis they argued that the decision involves retaining water in storage for use in later periods and that this form of insurance is appropriate for higher-valued water uses where reservoirs have low refill potentials or uncertain inflows. You and Cai (2008) extended Draper and Lund's approach to incorporate hydrological uncertainty into the marginal utilities of release and carry-over storage. Zhao and Zhao (2014) extended the analysis to a multiperiod model and found that the objective of a reseroiv operator was to ensure consistent marginal benefits across all time periods.

It should be noted that Figure 1 presumes a "target demand" at which point no further water is desired. This is a hydrological simplification of demand in that it does not recognise the relationship between quantity demanded and the price of water. However, it is on this basis that regulatory structures have been developed both in Australia and overseas. For instance, the service level obligations on water utilities set the frequency and severity of restrictions regimes that will be imposed in Australia. Presumebly this reflects an optimal hedging arrangement, but one that fails to account for demand's responsiveness to price.

The advent of reliable manufactured water creates an upper limit on social losses associated with reservoir failure, consequentially altering the decision facing a reservoir operator and created a new opportunity cost. Since a water supply source, such as a desalination plant, can be built with a defined number of years and to a fixed reliable quantity, the cost of maintaining a given level of reliabiltiy can be quantified.

Consider the following conceptual two-period model where a reservoir operate is required to maxmise total utility while maintaining a minimum level of water delivery, and with a range of augmention options (S_i^a) available to ensure that this minimum can be met. This situation can be described as:
:

$$\max U = TB_1 + TB_2 - Cost_i(S_i^a) \qquad (1)$$

$$s.t.$$

$$TB_j = f_j(Q_j) \qquad (2)$$

$$Q_1 + Q_2 = S + S_i^a \qquad (3)$$

$$Q_j \geq D^m \qquad (4)$$

Where U is utility, and TB_j is the total benefits of water released in period *j*. Costs *i* are the costs associated with augmentation *i* and there are 1, 2,…n possible augmentations that can be commissioned in the first period and be ready for use in the second period to produce quantity S_i^a, and D^m is the minimum level of demand that must be met.

It should be noted that this model allocates available water between demand in period one and period two. As such, the derived decision rules and outcomes will be functions of the predetermined initial stock, inflows and required final stock.

The Lagrangian for this program is:

$$L(Q_1, Q_2, S_i^a, n, \lambda_1, \lambda_2) = -f_1(Q_1) - f_2(Q_2) + cost(S_i^a) - n(Q_1 + Q_2 - S - S_i^a) + \lambda_1(D^m - Q_1) + \lambda_2(D^m - Q_2)$$

While complex, applying the Karush–Kuhn–Tucker (KKT) conditions under two scenarios shows that optimality is achieved when:

Scenario 1: Plentiful water

$$n^* = \frac{\partial f(Q_1)}{\partial Q_1} = \frac{\partial f(Q_2)}{\partial Q_2} \qquad (5)$$

This suggests that total benefits are optimised when marginal benefits today are equivalent to marginal benefits tomorrow when constraint (4) is not binding.

Scenario 2: Scarce water in period II

$$n^* = \frac{\partial f(Q_1)}{\partial Q_1} = \frac{\partial \mathrm{cost}(S_i^a)}{\partial S_i^a} \qquad (6)$$

Which suggests optimality is achieved when water is scarce in period two by charging the marginal cost of the augmentation in period 1. If a desalination plant has already been built, than the marginal cost of the agumentation operating cost; if plant to be built, then the marginal cost is the operating cost plus annual fixed cost for depreciation and interest.

Equations (5) and (6) are the first derivative of the total benefit function of demand, which sets demand for water as a function of its price. While hedges, and Australia's reliability framework, allocate water via restricitons it could be rationed via price, regulations or a combination.

It should also be noted that manufactured water supply sources require a lead to develop. As a consequence, it is necessary to evaluate the decision over two periods of a length associated with the construction time. For instance, a desalination plant may take four years to plan and construct, or approximately two years to construct it if planning has already been complete. This augmentation timeframe establishes the length of the two periods and is a critical factor in establishing the cost of reliability for a water supply system.

Hu et al. (2016) showed that extending the two period model to a multiperiod one results in utilitiy being optimised across all periods. So, if water is scarce in one period, the discounted cost of that needs to be incorporated in the first period price for water.

While conceptual, this is a real world problem. Consider the response of water authorities in California facing reduced inflows and uncertain future water supplies. As of 2006 there was a total of 21 proposed desalination projects under active consideration. This number had fallen to 19 in 2012 and, as of May 2016, was just nine (Cooley, et al 2016). That all these projects were not implemented suggests that they were short term responses to climatic conditions and not optimal investment strategies. A similar outcome occurred during the Millennium Drought in southeast Australia (2001-2009) when a range of urban centres built large desalination plants to supplement water supply systems that had previously been considered reliable. These desalination plants have not yet been used to their full capacity.

For the purposes of discussion, this paper will examine augmenting an urban water supply system through a manufactured water supply source, such as a desalination plant or recycling. However, this approach is relevant for quantifying the value of alternative water sources for any water supply system with reserve capacity, where reservoir failure causes economic loss to users and where there are alternative water supply sources, such as an agricultural reservoir with access to inter-basin water transfers.

SIMULATION

Equations (1) through (6) set out a deterministic way for attrributing the cost of reliability. An alternative method, more applicable to real world scenarios, is to quantify the cost of reliability regulations via simulation. This paper sets out the methodology for doing so and for comparing its sensitivity with its key determinantes: the amount of water being met, the probability associated with meeting it, and the lead time for the augmentation that underpins its reliability.

The methodology is demonstrated through an application to a single reservoir system that can be augmented with a desalination plant of scalable but unknown size. This system is sized to be a reasonable representation of a major metropolitan water supply and we use an aggregation of the inflows to the four main reservoirs constituting the urban water supply of Melbourne: the Thomson, Upper Yarra, O'Shannassy and Maroondah reservoirs. Data were available to form a single 97-year (1913-2010) reconstructed streamflow data series. An annual lag one autoregressive AR(1) model with parameter uncertainty was fitted using the Stochastic Climate Library (Srikanthan, et al. 2007) and 200,000 synthetic 50 year hydrological realisations were produced.

Table 1: Stylised water supply system key statistics

Illustrative example water supply system	
Annual demand	90 per cent of mean inflow, 500 gigalitres per annum
Reservoir size	Four times annual demand, 2,000 gigalitres per annum
Hydrological model	AR(1) from the Stochastic Climate Library
Number of realisations	200,000
Length of realisations	50 years
Service level obligation	annual risk of zero storage never more than 0.1%
Augmentation option	To build a desalination plant within two years (t_{lead} = 2)
CAPEX	\$23,300/ML/a
OPEX	\$500/ML
Restrictions regime	Demand reduced to 90 per cent when storages are at 55% and to 80% when storages are at 33%.

An annual time step simulation of the system was undertaken to simulate water in storage, St, at time, t, from a selected initial level of water in storage, S0, reservoir inflows, Qin,t, demand, Dt, and water produced by the augmentation, Qaug,t. Prior to calculating St+1, the spills, Qspill,t, from the system and supplied water, Qsupply,t, are calculated as follows.

$$Q_{supply,t} = \min(D_t, S_t + Q_{in,t} + Q_{aug,t})$$

$$Q_{spill,t} = \max(S_t + Q_{in,t} + Q_{aug,t} - Q_{supply,t} - S_{max}, 0)$$

$$S_{t+1} = S_t + Q_{in,t} + Q_{aug,t} - Q_{supply,t} - Q_{spill,t}$$

In essence, S_{t+1} is constrained such that $S_{t+1} \leq S_{cap}$ and $S_{t+1} \geq 0$, where S_{cap} is the total storage capacity.

It is assumed that there is an option to augment the water supply system exists and that the system will be augmented if S_t falls below a threshold storage

S_{aug}. It is also assumed that the augmentation will take a known amount of time t_{lead} to commission and that it will have a capacity C_{aug}. The augmentation decision status is represented by A_t which is zero before the decision to augment has been made and one thereafter. Thus A_t becomes 1 at the first time step where $S_t \leq S_{aug}$ and this time is t_{aug}.

The probability of failure in any given year for the given S_0 is then calculated as:

$$P_{fail,t} | S_0 = N(S_t = 0) / N$$

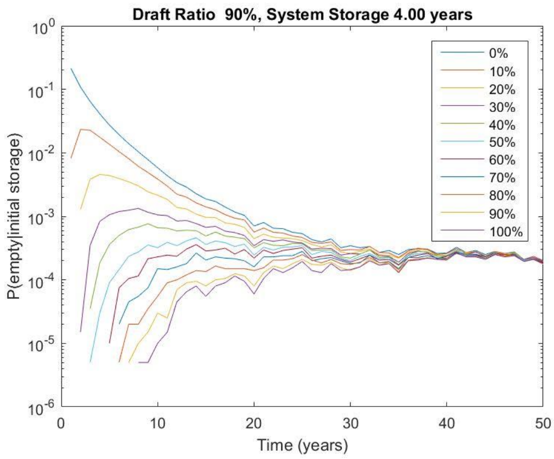
where N is the total number of realisations and $N(S_t = 0)$ is the number of realisations where $S_t = 0$. The short-term annual reliability given S_0 can then be calculated as

$$R_{yplan} | S_0 = 1\text{-max}(P_{fail,t}) \text{ for } t \leq y_{plan}$$

where y_{plan} is the planning horizon.

The threshold storage S_{aug}, is determined when the short term reliability falls below that stipulated in the service level obligations. Figure 2 outlines the annual probability of failure for a given initial storage. S_{aug} is found by identifying the level of storage where the service level obligations are violated for the timeframe of the augmentation.

Figure 2: Probability of failure in any given year



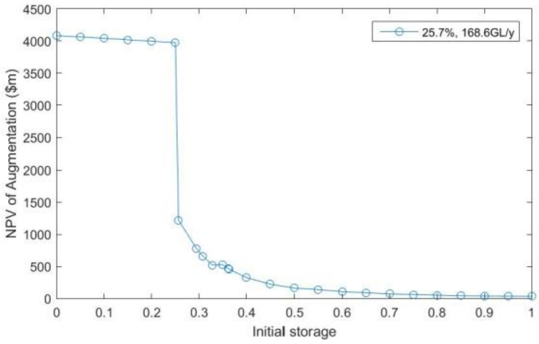
In the base case, the requirement to meet restricted demand with a 0.1% probability of failure means that S_{aug}, occurs when storages are 25.7 per cent.

It should be noted that even in the highly reliable system described in this simulation, initial conditions take decades to converge on the long run expectations, highlighting the importance of short term risks in the water supply system.

As the optimality conditions in Scenario 2 suggest, the marginal cost of a future augmentation driven by resource scarcity should be incorporated in today's price.

When storages are at S_{aug},, then the marginal cost is the expenses associated with the augmentation. As the level of water in storage increases above S_{aug}, the probability of needing to augment declines. However, there is a possibility that storage levels will fall to the level in the future. The marginal cost of augmetnation, for storages above S_{aug}, is the time and probability discounted cost of augmenting in the future, referred to as the augmentation liability for a given level of storage. Examining this across the range of initial storages outlines the costs associated with mainintaing reliability for the water supply system (6) as a whole, described below for the base case.

Figure 3: Augmentation liability



The reliability standards of the base case require a desalination plant capable of producing 168.6 gigalitre per year to be built when storages are at 25.7 per cent.

Based on Scenario 2, equation (6), economic efficiency is achieved when the price of water, or restrictions that achieve this shadow price, reflect the marginal cost of augmentation. So even though water storages may not be at $S_{aug\ min}$ the time and probability discounted cost associated with storages falling to this level need to be incorporated within all storages at which it is applicable.

The steps to calculating the augmetnation liability curve are outlined in figure 4.

Costing reliability involves explicitly comparing alternatives to its key parameters, notably the magnitude of demand being met relative to stream inflow, the acceptable probability of not meeting that reliability, and the timeframe of the augmentation option. As a consequence, this paper will examine these parameters:

- D^m by describing the augmentation liability curve for restricted and unrestricted demand.
- Service level obligations
    - 0.1% chance of failure;
    - 0.1% chance of failure; and
    - 0.5% chance of failure.

- Augmentation timeframe:
    - Five year leadtime;
    - Four year leadtime;
    - Three year leadtime; and
    - Two year leadtime.
    - .

RESULTS

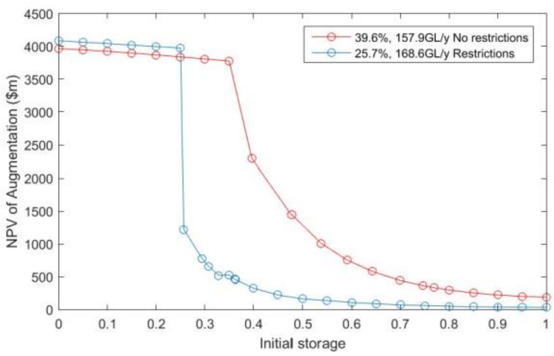
Minimum demand

This paper assumes that urban areas require a basic minimum amount of water. The role of an urban water utility is to use naturally occurring and manufactured water to meet this demand while minimising infrastructure investments.

How much water utilities *must* meet is an important driver of the augmentation liability as it forces augementations. The very basic water necessary for life in developing countries has been estimatedas being 20 litres per capita per day for survival and domestic hygiene purposes (WHO/UNICEF, 2000). However, the level of water deemed essential to meet the non-agricultural needs of developed economies has been estimated to be 135 litres per person per day (Chenoweth, 2008).

To examine what the cost of changing the level of demand being met through the reliability standards, the base case, where restrictions are applied at 50 per cent, is compared with the augmentation liability when no restrictions are applied. It should be noted that without restrictions the water supply system no longer meets the long term reliability service level obligations.

Figure 5: Augmentation liability curves with and without a restrictions regime



This shows that when demand is unrestricted, S_{aug}, occurs when storages are 39.6 per cent. Since this is occuring at a higher level of storage, the desalination plant built is actually smaller, requiring a plant of 158 gigalitres per year. Since the water supply system no longer meets the reliability standard, there is a noticable augmentation liability for all levels of storage.

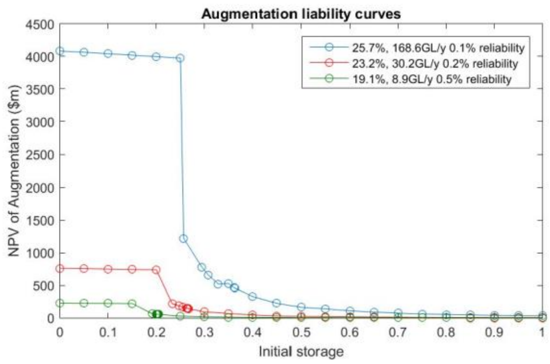
Taylor et al (2016) showed how the augmentation liability rapidly increases as annual demand approaches mean annual inflows.

Service level obligations

Service level obligations represent the social trade off between investment in infrastructure and the risk of running out of water. This trade off is expressed in the acceptable probability of reservoir failure.

It should be noted that this probability can never be completely eliminated. However, for a given set of hydrological expectations, a relationship between investment and risk can be quantified and examined.

Figure 6: Augmentation liability curves, different probabilities of failure



Given the water supply system is highly reliable, extreme events drive the augmentation liability. As a consequence, doubling the level of acceptable risk, to 0.2 per cent, results in the trigger threshold falling from 25.7 per cent to 23.3 per cent. Howerver, the augmentation required at this threshold declines more dramatically, from a desalination plant capable of producing almost 170 gigalitres to one that produces just over 30 gigalitres a year. When the acceptable level of risk increases to 0.5 per cent, then the trigger storage threshold falls to 19.1 per cent and the required desalination plant needs to produce 9 gigalitres per year.

As this shows, the level of risk that society tolerates has a very significant influence on the cost of reliability.

Augmentation timeframe

The timeframe associated with an augmentation can be broken down into a series of discrete stages that represent different actions required to build it. Undertaking some of these actions can bring reduce the lead time of an augmentation. Taking the action to reduce the lead time represents purchasing a “real option”.

A number of commentators have suggested that the urban water sector use a real options approach to augmentation (PC, 2011, Clarke, 2012). This approach involves breaking the entire augmentation project down into discrete sections and undertaking them as and when they are appropriate. A key benefit of this approach is that it allows more responsive decision making. If a drough breaks, an augmentation does not need to be undertaken.

The Productivity Commission (2011) review of the Urban Water sector specifically recommended that using a real options approach to urban water augmentations would have reduced the costs of supply by $1.1 billion over the course of ten years for Melbourne and Perth.

One challenge associated with this approach is that purchasing a real option is costly. These costs are explicit, upfront and can be challenging to implement. Quantifying the benefits of reducing the lead time can help inform the public debate.

The base case assumed a two year construction period. If this was extended, for instance there was a planning and design phase, then the augmentation would need to be triggered earlier to ensure it is available when storages potentially “run out.” The following chart describes the augmentation liabilitity curves when the lead time for building a desalination plant is extended.

As the lead time increases, both the trigger threshold, S_{aug}, and the probability of reaching it increase. While the size of the emergency augmentation remains the same, how often it gets built, and how much water is in storage when it is built, both increase as the lead time increases.

Changing lead time		
Lead time	**Expected Augmentation liability ($m)**	S_{aug}
2 years	$ 3,975	25.7%
3 years	$ 4,712	29.4%
4 years	$ 5,071	30.8%
5 years	$ 5,424	32.8%

As this table shows, reducing the amount of time it takes to augment a water supply system sigificantly reduces the cost of maintaining its reliability. However, these benefits are not explicit, while the costs of undertaking actions that reduce the time it takes to augment the water supply system are explicit.

CONCLUSSIONS

Having the capacity to augment water supply systems means that the cost of meeting reliability standards can be objectively evaluated. This creates the opportunity to examine the potential trade-offs involved with alternative augmentation options or reliability frameworks.

Quantifying the benefits associated with purchasing an augmentation option can help justify the sometimes difficult political decisions that this involves.

The augmentation liability associated with a given reliability standard can be used to inform operation decisions. It also acts as a means of informing the community about hydrological risks via an objective economic measure.

The approach outlined in this paper can be used to evaluate the costs of meeting service level obligations. This provides a methodology for quantifying hydrological risks for urban centres. It also provides an approach for evaluating the trade-offs with alternative service level obligations which could be applied to a wide range of communities.

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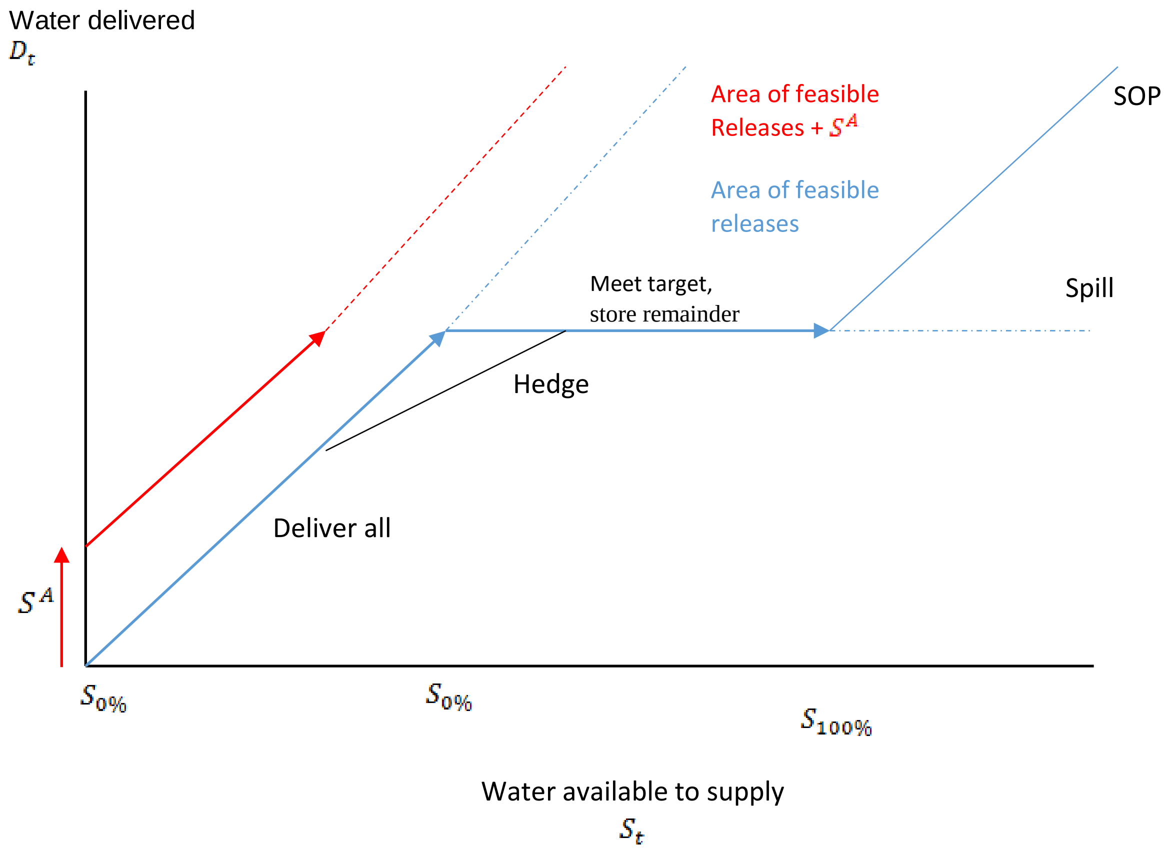

Figure 1: The Standard Operating Policy, hedging and augmentation.

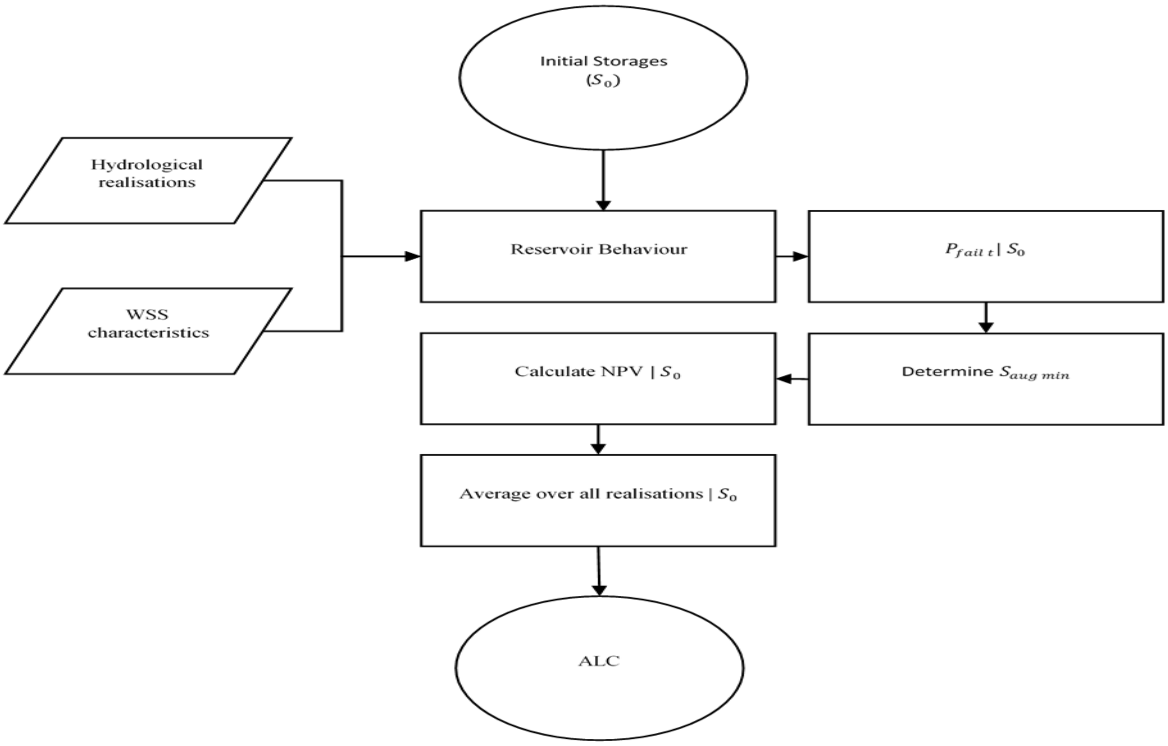

Figure 4: Flow chart for determining the augmentation liability associated with initial storage levels