THE COSTS OF DROUGHT IN URBAN WATER SUPPLY PLANNING

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ABSTRACT

Droughts can have significant and varied impacts in urban areas. Such impacts range from the direct costs of water interruptions on businesses, the intangible costs of water restrictions on households, to the environmental impacts of increased water abstraction. It is therefore challenging to assess the full range of economic costs of a drought.

This study presents a practical framework to assist urban water suppliers with this challenge. The framework supports suppliers to identify relevant drought impacts, apply suitable methods to quantify the costs of these impacts, and then integrate such costs into their long-term water supply planning. A supplier can use these results not only to inform the optimal level of service for its supply network but also to inform decision-making during a drought.

This paper considers the application of the framework to Wellington Water. Under the framework, Wellington Water's current 2%/1 in 50-year annual shortfall probability level of service sits within the range of optimal level of service results, albeit with some limitations and assumptions that need refining. This initial outcome was surprising in light of recent studies into the cost of drought in the United Kingdom that have recommended significant improvement in levels of service.

The case study illustrates the difficult choice a supplier may face during a severe drought between cutting off water to some customers or taking water beyond environmental limits, with high environmental costs. The results indicate that in this case taking water beyond environmental limits likely has lower economic costs, however the research identifies several challenges and uncertainties in linking river abstraction with environmental costs.

This paper identifies areas of further research to improve understanding of the drought impacts and community preferences to aid suppliers to make more well informed decisions in this complex but increasingly important area of network planning.

KEYWORDS

Water supply planning, drought, resilience, asset management

PRESENTER PROFILE

Associate Professor Asaad Shamseldin has considerable research, consultancy and technology transfer experience in the field of hydrology and water recourses. He acted as a reviewer for engineering design guidelines both nationally and internationally. He also served as editor for international journals. His research focuses on innovative predictive modelling combined with an experimental approach to advance scientific knowledge. His work covers the areas of climate and land-use changes, urban water management, catchment hydrology, global water cycle, natural hazard engineering and risk and uncertainty analysis.

1 BACKGROUND

Assessing the cost of drought is becoming more important to water suppliers as climate change increases the frequency of drought events. In 2021, the United Kingdom Environment Agency updated its water resource planning guidelines to require water supply networks to be resilient to a 1 in 500-year return period drought, up from 1 in 200 years. The Agency determined that the billions of pounds required to enhance supply to meet this target was less than facing the cost of drought, specifically the cost of emergency water supply.

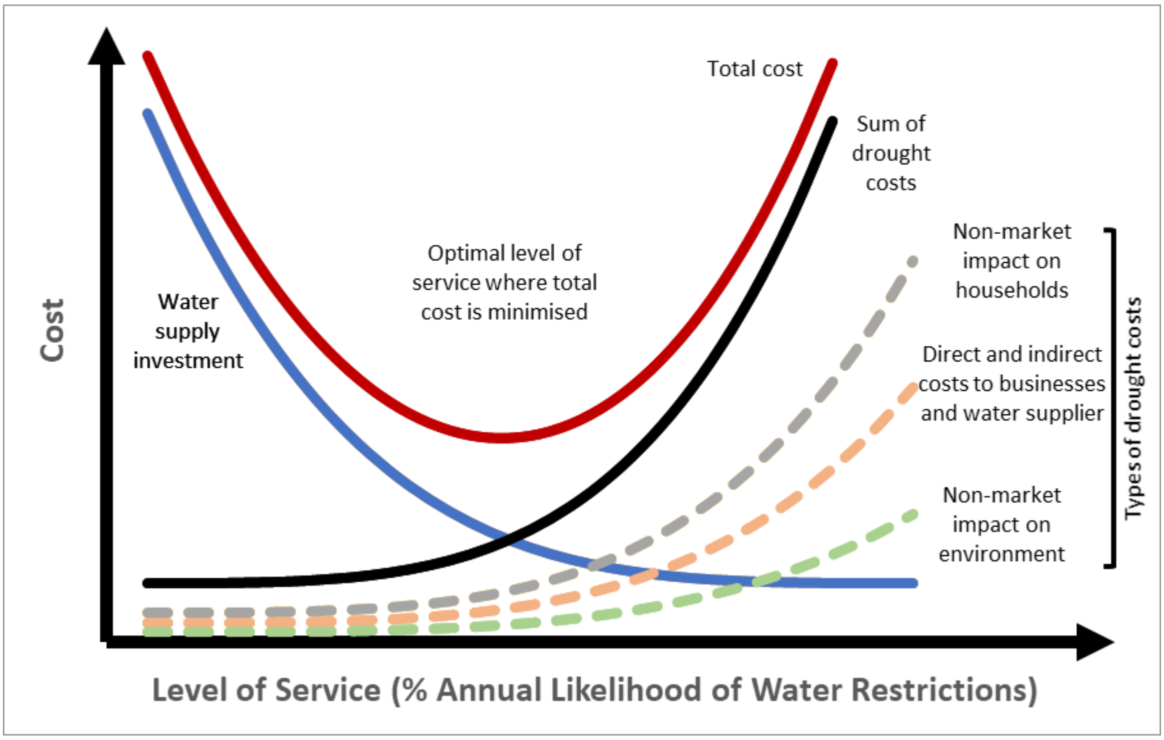
Drought resilient water supply networks provide value to suppliers by reducing the costs associated with drought events. The Agency's decision illustrates a key trade-off for suppliers in network planning and investment decisions: weighing up the relative costs of drought with the costs of enhancing water supply that might go unused.

This trade-off is demonstrated in Figure 1, which shows the relationship between water supply investment and the cost of drought. The optimal level of investment is where total cost is minimised. As level of service is expressed in annual likelihood of water shortfall, a lower level of service will have a lower risk of drought but will require greater water supply investment. The figure also shows the importance of considering all relevant types of drought cost. Excluding some costs would result in underinvestment in water supply infrastructure.

This study presents a practical framework for water suppliers to integrate the costs of drought in water supply planning. Current level of service targets for water supply in New Zealand appear to be relatively ad hoc and largely based on professional engineering judgement for each region. Such an approach is understandable given the complexity of assessing the full range of possible costs, particularly the diverse range of methods required. However, there is a risk of underestimating costs. This framework aims to complement existing approaches to provide a practical way to ensure a comprehensive assessment of all drought costs.

This paper is divided into three parts. First, the paper identifies the range of drought costs in urban areas and discusses suitable methods for assessing each of these costs. Figure 1 shows the importance of considering the full range of drought costs. Second, the study considers the unique characteristics of urban drought that affect the estimation of the costs of a single drought event in the short term. The paper then considers how these short-term costs fit into longer term water supply planning. Finally, this paper discusses the learnings from applying the framework to Wellington Water's supply network.

Figure 1: Optimal level of water supply investment considering the full range of drought costs



2 FRAMEWORK FOR ASSESSING DROUGHT COSTS IN WATER SUPPLY PLANNING

2.1 INTRODUCTION

The significant amount of investment involved in water supply requires decisions be made within a principled framework that enables comparison between the costs of a drought with the costs of building a resilient network. To this end, the present research develops a framework taking into account existing approaches, economics literature, water regulator standards and industry studies. The framework recognises the unique features of drought in urban areas.

The aim of the framework is to provide a practical approach for water suppliers to integrate all drought costs into their supply planning.

2.2 TYPES OF DROUGHT COST

Drought impacts urban areas in multiple ways. This study aims to identify and quantify the economic impacts of drought in monetary terms. The framework measures direct costs, such as lost production at a factory without water, as well as wider indirect costs, such as the upstream and downstream impacts on the factory's suppliers and customers.

The framework also seeks to quantify non-market or intangible costs that cannot be bought and sold in a market so do not have an observable monetary value. Two of the most significant impacts of drought in urban areas are the impact of restrictions on households and environmental degradation from water abstraction. Communities clearly place a value on avoiding these impacts and there are established non-market valuation techniques can be used to estimate them in monetary terms. Compared to more rural agricultural areas, a much greater portion of total drought costs in urban areas are non-market costs.

Table 1 shows the range of drought costs for urban areas. Each of these costs can significantly affect the total cost of drought. As such, any comprehensive assessment of the cost of a drought should at least consider these costs. Previous studies have focused on one or a limited number of costs, resulting in an underestimation of total drought costs.

Table 1: Types of drought costs in urban areas. Source: own elaboration from Meyer et al. (2013)

Affected Group	Cost Category	Cost Description
Households	Non-market	Welfare losses from restrictions – how much households would be willing to pay to avoid water restrictions
		Environmental impacts of abstraction – Ecology, recreation, spiritual or cultural values
	Direct	Public health costs from water shutdowns. Boil water orders, impact on healthcare facilities*
Non-household customers – businesses, industry, agriculture, public sector	Direct	Direct economic losses such as loss of production
	Indirect	Flow on effects from direct losses such as upstream/downstream impacts on suppliers and customers or unemployment
Water Supplier	Direct	Cost of emergency water to avoid severe emergency restrictions, unplanned response costs, fines from regulators
		Loss of revenue from less water supplied
		Cost of communication campaigns to during restrictions
		Political fallout. Cost of supplier reform or fast-tracking capital projects that would not have been done otherwise*
	Non-market	Reputational/political cost of water restrictions*

*No previous studies were found quantifying these costs.

For the purposes of the framework the relevant costs are only those that arise as a result of a water supplier's actions. That is, there is a base level of actual cost outside a supplier's control. Such non-variable costs are disregarded. For example, there may be environmental impacts from low flows in a stream during a drought (a non-market cost). The framework does not assess the cost of the naturally occurring low-flows. However, the framework would measure the costs of any additional water abstraction undertaken by a supplier because that non-market cost is caused directly by the supplier.

2.3 METHODS FOR ASSESSING DROUGHT COSTS

Estimating the costs of drought in urban areas can be complex as there is no single method that can be used to estimate all of the costs shown in Table 1. Costs must instead be estimated separately using a variety of different methods.

Table 2 summarises a selection of methods for assessing drought costs. Methods are ordered based on their relative effort based in resources and time to complete, which generally corresponds with increased accuracy and robustness. Lower effort/less robust methods can be applied first to give an indication of the order of magnitude of different costs to help prioritise further research.

The methods a supplier selects to estimate drought costs depends on the types of customers being supplied and available resources and time. Costs that are most significant to the total drought costs should be prioritised. An area with predominantly residential customers should place more effort to estimating the non-market impacts on households and the environment. Less robust methods may be able to be applied to direct and indirect costs.

A water supplier to industrial or agricultural customers would have greater focus on direct costs and the indirect impacts on the wider economy. In this case it would be worthwhile to invest the resources on a more robust method of estimating indirect costs such as input-output or computational general equilibrium modelling. Non-market costs may be negligible to the total drought cost.

Suppliers that have a mixture of different customers will need to split effort across multiple methods.

Table 2: Summary of selected methods for assessing drought costs

Type of Cost	Method for Estimating Cost
Direct	Estimate GDP impact per sector based on previous studies
	Market valuation techniques
	Drought damage function
Indirect	Economic amplification ratio from literature
	Input-output modelling
	Computation general equilibrium modelling
Non-market	Benefit transfer – direct transfer from primary stated preference or revealed preference studies (to understand societies willingness to pay to avoid impacts of drought)
	Benefit transfer – transfer function or meta-analysis, from primary stated preference or revealed preference studies
	Original stated preference or revealed preference study

Legend

Lower effort/lower robustness
Higher effort/higher robustness

Direct Costs

Direct costs can be scaled off previous drought studies, estimated based on market prices such as a loss in water supplier revenue from less water supplied, or by making assumptions that link water restrictions with a percentage decrease in output by industry.

Indirect Costs

Direct costs need to first be estimated and split by industry. A multiplier to direct costs based on industry direct costs may be appropriate if indirect costs are relatively low. More advanced techniques include input-output and computational general equilibrium modelling which model the complex interactions of water shortage that ripple through the wider economy. These approaches can be time and resource intensive and require specialist knowledge to apply.

Non-market valuation methods

Non-market valuation is a well-established field that is regularly used in decision-making to quantify the preferences of the community. Methods include stated preference techniques that ask respondents to state their preferences between hypothetical trade-offs, and revealed preference studies that observe behaviours, such as estimating the recreational values of a river by people's travel costs to get there. Primary studies are expensive and time consuming and require technical expertise to apply.

Benefit transfer is the process of transferring values from relevant primary studies to the study area. There are a benefit transfer approaches ranging in complexity and robustness. Accurate transfers rely on the quality of the primary studies and careful consideration of the characteristics of the original sites and the study site.

2.4 DROUGHT COSTS FOR A SINGLE DROUGHT EVENT

Figure 2: Drought cost curve in the short run for a single drought event

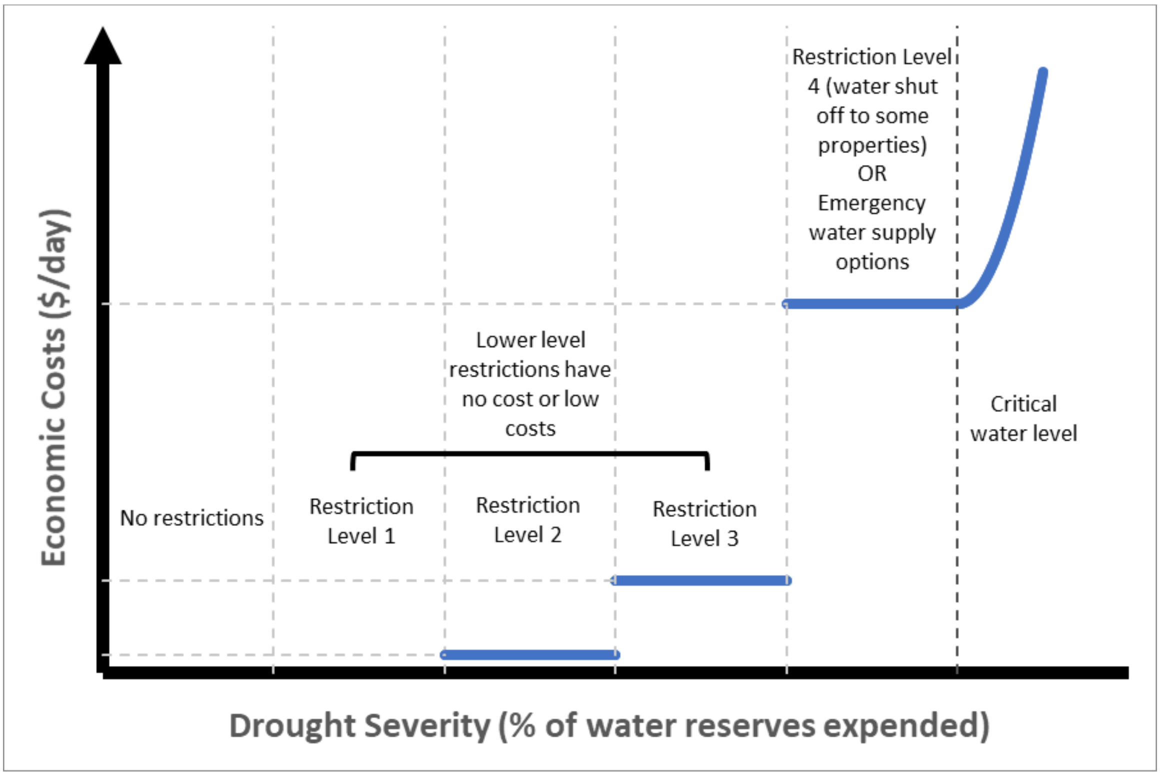


Figure 2 shows:

- The costs of drought increase as a discrete step function as a drought becomes more severe and the water supplier makes the decision to apply increasingly severe water restrictions.
- The impacts of drought are only felt by consumers once a supplier decides to apply restrictions. Under this approach, it is conceivable that the impact of droughts can be avoided entirely through sufficient investment in storage or other reliable sources such as desalination.
- Lower-level restrictions such as limiting garden watering have low costs associated with them. Higher level restrictions where water is shut off to

customers has a much higher cost. Costs increase exponentially once water reserves are depleted.
- An alternative assumption proposed by the United Kingdom National Infrastructure Commission (2018) is that shutting off water to a city would be seen as politically unthinkable. Suppliers and governments would be under intense pressure to not shut off water. Instead, they would source emergency water through any means possible with high financial and environmental costs. For example, trucking water, abstraction from rivers or aquifers beyond environmental limits. Shutting off water or emergency water supply both have high costs.
- The cost of restrictions and cost of emergency water can be substituted for each other within the framework. Water restrictions have an expected reduction in demand associated with them. If this same reduction in demand can be supplied by emergency water, the restriction does not need to be applied.
- Tying the cost of drought to the number of days spent at each level of restriction simplifies integrating the cost of drought into water supply planning.

2.5 INTEGRATING DROUGHT COSTS IN WATER SUPPLY PLANNING

The net present value (NPV) is estimated for both water supply costs and drought costs over a supplier's typical planning period of 20 to 50 years. A higher level of service (lower likelihood of water shortfalls) will have a higher net present cost as water supply investments must be installed earlier in the planning period. The relationship between water supply investment and the cost of drought is shown in Figure 1.

Water suppliers face the challenge of having to commit to substantial supply investments that can take years to design and build, as well as facing significant uncertainties such as climate change and population growth. Regardless of the approach taken to decision-making under uncertainty, minimising total economic cost will be an important objective and therefore there is a need to understand drought costs. Methods for dealing with uncertainty include relatively straightforward measures such as applying a headroom factor as well as more complex multi-objective optimisation methods that seek robust and flexible combinations of supply options.

Understanding drought costs can also inform the timing of water restrictions. For example, applying early but less severe restrictions may be preferable to reduce the risk of more significant and costly restrictions.

An improved understanding of the costs of water disruptions would also be useful in assessing the impacts of events such as earthquakes or a treatment plant failure.

3. WELLINGTON WATER CASE STUDY

The framework for assessing drought costs in water supply planning was applied to a case study with Wellington Water who supply water for Wellington, Lower Hutt, Upper Hutt, and Porirua cities. Note that Wellington Water is currently in the process of reviewing their drought management and future water supply planning policies. Inputs are used in this study are estimates based on professional judgement and may not reflect final policy. System performance and future water supply costs are from a 2020 study and are also currently in the process of being revised.

The Wellington region is an interesting case study as the region receives frequent rainfall throughout the year, even in summer. As a result, there is a relatively little storage, and the system is vulnerable in dry periods longer than three months allowing little warning before a drought. This is in contrast with other areas such as in Australia where droughts can last for multiple years, or the United Kingdom where a dry period of 8-18 months would be expected to cause severe drought conditions.

Methods of lower effort/lower robustness from Table 2 were applied due to time and data constraints to demonstrate the framework. Many of the inputs were gathered from overseas primary studies and have a relatively high uncertainty associated with them.

The case study investigated two different approaches to the following question: what would suppliers do in the event of a severe drought?

- Severe water restrictions shutting off water to some customers
- Emergency water supply with high environmental costs

3.1 SEVERE RESTRICTION APPROACH

Wellington Water's drought management plan proposes a 67% decrease in household demand in its highest ("Level 4") water restrictions. Effectiveness of previous restrictions in Wellington and studies from the United Kingdom suggest a decrease of this scale is unlikely to be possible through voluntary reductions alone (AECOM, 2016; DEFRA, 2013). It was assumed that rotating water cuts to sections of the network would likely be required. This would have significant impacts on the Wellington Region, with the largest impacts being the non-market impact on households and direct costs to non-household users.

Total drought costs per day were estimated at:

- $0.7-1.9 million/day of Level 3 restrictions
- $41-95 million/day of Level 4 restrictions

Household Impact

A literature review of non-market valuation studies showed households have a high willingness to pay (WTP) to avoid severe restrictions. They place a smaller value on avoiding bans on residential outdoor use, like Wellington Water's Level 3 restrictions. A very low value was placed on avoiding restrictions less severe than this so these were not considered further.

Only a limited number of the reviewed studies were able to be applied within the framework shown in Figure 2, in terms of costs per restriction level per day. A challenge is that WTP to avoid water restrictions can be expressed in multiple ways. Some Australian studies referred to WTP for a reliable water supply or WTP to avoid restrictions entirely without specifying what those restrictions entail. Others focus on WTP to avoid restrictions per quarter or year without specifying the expected number of days of restrictions (Cooper, Burton, & Crase, 2019; Wilson et al., 2021). This limited the number of studies that were able to be considered.

An ideal primary study would also have results expressed as a parametrised function of the site characteristics. This function could then be adjusted to the characteristics of the Wellington region. Studies with results like this indicate that WTP to avoid water restrictions is a function of income, education, number of people in a household and whether the household has a pool or a lawn. Unfortunately, these studies were not able to be converted to the cost per restriction level per day format.

Wellington Water's Level 3 and Level 4 restrictions (assuming rotating water cuts) are broadly similar to restriction levels in the United Kingdom. A 2011 London study was selected as the most appropriate study to apply (Metcalfe & Baker, 2011). This indicates a WTP of $5 (NZD, 2021) per business per day to avoid Level 3 restrictions and $129 to avoid Level 4 restrictions.

A key risk in applying these values is the possible non-linear relationship between WTP to avoid one day of restrictions and drought duration. Level 4 restrictions are expected to be applied in the UK for up to three months, whereas in Wellington severe restrictions of three weeks are more likely. It is possible that households do not mind shorter duration restrictions, and WTP increases as restrictions are longer. Alternatively, there could be a lump sum WTP for households to avoid restrictions of any length, increasing the average cost per day for shorter duration droughts.

Non-Household Impact

Rotating water cuts would have a severe impact on non-household water users. Industries such as manufacturing, food services and construction would be unable to operate without water supply. Offices would also likely have to shut without water for sanitation and fire sprinklers.

Two methods were used to estimate non-household impacts, with both producing estimates within 10% of each other. Results from the Metcalfe and Baker (2011) were again applied. These indicated a WTP of a $117 (NZD, 2021) per household per day to avoid Level 3 restrictions and $2057 to avoid Level 4 restrictions. The impact of Level 3 restrictions were not applied as Wellington Water's drought management plan aims not to impose restrictions on non-households at Level 3.

An alternative approach was to assess the effect of water shortages on GDP per day for each type of industry in the Wellington Region. An average decrease in regional GDP of 29% per day was estimated. Both methods are high level estimates.

A large portion of the Wellington region's GDP is from office-based knowledge industries. Previous studies into the impact of water shortages were prior to the COVID-19 pandemic where water shortages would likely shut offices and significantly reduce productivity. In an era of working from home, the impact of short duration shutdowns on non-households may have been overestimated.

3.2 EMERGENCY WATER SUPPLY APPROACH

The emergency water supply approach assumes that cutting off water supply to households is politically unthinkable. It was assumed that Level 3 restrictions banning outdoor water use would still be applied. Approximately 30-50 megalitres per day (ML/d) of emergency supply would be required to avoid the most severe Level 4 water restrictions.

Total drought costs were estimated at:

- $0.7-1.9 million/day of Level 3 restrictions (same as for severe restriction approach)

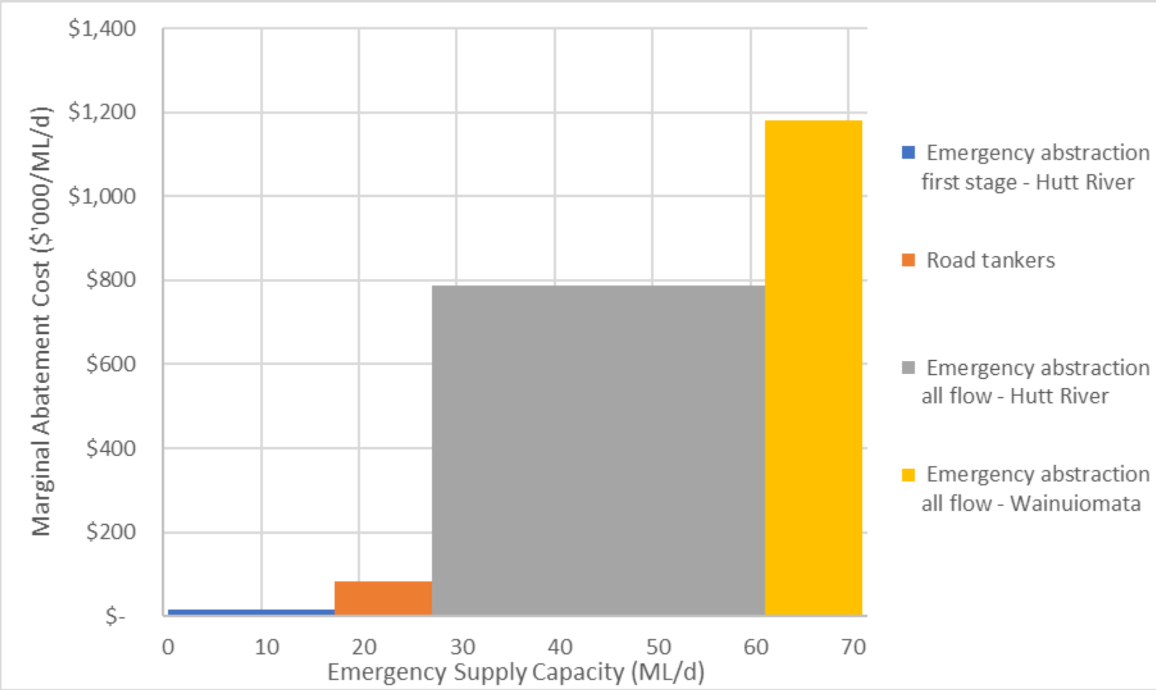
- $5-65 million /day of emergency water supply to avoid Level 4 restrictions

Emergency water supply options in Wellington are limited due to the short duration and short lead times to a drought. Feasible options identified are limited to trucking water and abstraction of water sources above environmental limits. Overseas studies have proposed options such as shipping water by sea and emergency desalination plants.

Figure 3 shows an estimation of the marginal cost curve for emergency water supply. Suppliers would successively apply options starting from the lowest marginal cost to reach the required emergency supply, as outlined below:

- The first stage is to take one third of the permitted minimum residual flow at the Hutt River intake. This was done for three weeks in 2013 with minimal additional long term environmental impact, noting that there is an existing base level of degradation in the river from abstraction. (Clapcott, 2020).
- Trucking up to 10 ML/d of water from various surface sources into the existing storage lakes was considered feasible (Atkins, 2018; Hutchison & O'Meara, 2012). Water tankers and milk trucks could be utilised at relatively short notice.
- Take all flow at the Hutt River intake. This occurred multiple times prior to the current consent was obtained in 2001. This would dry the river bed for approximately 600 m before it is joined by tributaries.
- Further options include taking all flow from the surface sources that feed the Wainuiomata treatment plant and taking groundwater from the Waiwhetū aquifer beyond safe limits. Additional water from the water from Waiwhetū aquifer was not considered sensible given the very high potential costs from saltwater intrusion in the aquifer.

Figure 3: Marginal cost curve for emergency water supply options



Application of the framework illustrates the challenge of quantifying the environmental impacts of emergency abstraction. There are two layers of uncertainty. First, the environmental impacts of taking water beyond minimum environmental flows need to be estimated. Then the value of the impact needs to be estimated.

The relationship between water abstraction and environmental impacts is not linear in volume or in time. This is illustrated in the Hutt River where taking flow past environmental limits for a short duration was found to have minimal additional long term environmental impacts. Taking all the flow in the river for a short period will certainly have greater impacts on environmental values such as ecology and recreation, but it is difficult to determine how much.

There are New Zealand non-market valuation studies into people's willingness to pay to improve a range of environmental values related to freshwater, namely water clarity, human health risk (swimability) and ecological quality. These have been used to assess policies such as quantifying the long-term benefits of fencing waterways from livestock as part of the 2020 National Policy Statement for Freshwater Management. The value people place on environmental values can be highly site-specific and no WTP studies were found for the Hutt River.

The challenge in applying these types of values is they are based on long term changes in water clarity, swimability and ecology, but it not clear how long it would take for these values to recover in the event of taking all the flow from the Hutt River during a drought. A wide distribution of possible values were tested as part of the sensitivity analysis.

Further studies into the environmental impacts of emergency abstraction from the Hutt River and the WTP of Wellington Water's customers to avoid these impacts would help improve these estimates.

Transporting water by tanker was a relatively cheap option but with limited capacity. It was assumed that environmental costs would be minimal if the 10 MLD take was spread between surface sources in the region.

Te Mana o te Wai

The drought cost framework considers the values and preferences of the community but does not directly consider the views of tangata whenua including Te Mana o te Wai. A study by Miller, Tait, and Saunders (2015) found that Māori have approximately 40% higher WTP to improve environmental values than the wider community. The study where the environmental values are sourced included a proportional number of Māori. Other studies note the difficulty of adequately capturing Māori values within an economic framework and that some Māori do not find the concept of quantifying these values acceptable (Harmsworth & Awatere, 2013).

Taking water beyond environmental limits clearly violates the hierarchy imposed by Te Mana o te Wai of prioritising the health and well-being of water above the health needs of people (drinking water) and economic wellbeing.

The challenge during a drought will be to balance between the principles of Te mana o te Wai and political pressure to not shut off people's water. Both may be seen as unacceptable. There is a level of abstraction beyond environmental limits that appears to have minimal additional impact on the health of the Hutt River if done for short periods. An improved understanding of where this level is would help inform this balance.

3.3 APPLYING THE DROUGHT COST FRAMEWORK

Four level of service (LoS) targets for the Wellington Water network were tested over a planning period from 2020 to 2050: 0.5%, 1%, 2% and 4% annual water shortfall probability, equivalent to 1 in 200, 1 in 100, 1 in 50 and 1 in 25 year levels of service respectively. The aim was to find the optimal level service where total cost is lowest. Testing a LoS less than 0.5% was not possible with the 2020 data that was available.

The water supply investment curve is the NPV of the capital and operational costs of future water sources. All other Wellington Water costs were assumed to be identical between LoS options so were not considered. Reducing the risk of water shortages results in a higher NPV as new sources have to be built earlier in the planning period. Supply-side investments such as new water sources or demand side investments such as water meters are treated the same. Both improve LoS and have associated Capex and Opex costs.

3.4 RESULTS - OPTIMAL LEVEL OF SERVICE

Figures 4 and 5 show the results from the severe restriction approach and the emergency water supply approach respectively. Figure 6 shows the distribution of results from the two approaches. The lower spike in results represents optimal level of service less than 0.5%.

The severe restriction approach suggests a higher optimal level of service (lower shortfall probability) with a median of 1.5%. A median level of service of 2.8% is suggested by the emergency water supply approach.

Figure 4: Results for severe restriction approach. Box and whisker plot of optimal level of service (minimum total cost) is overlaid

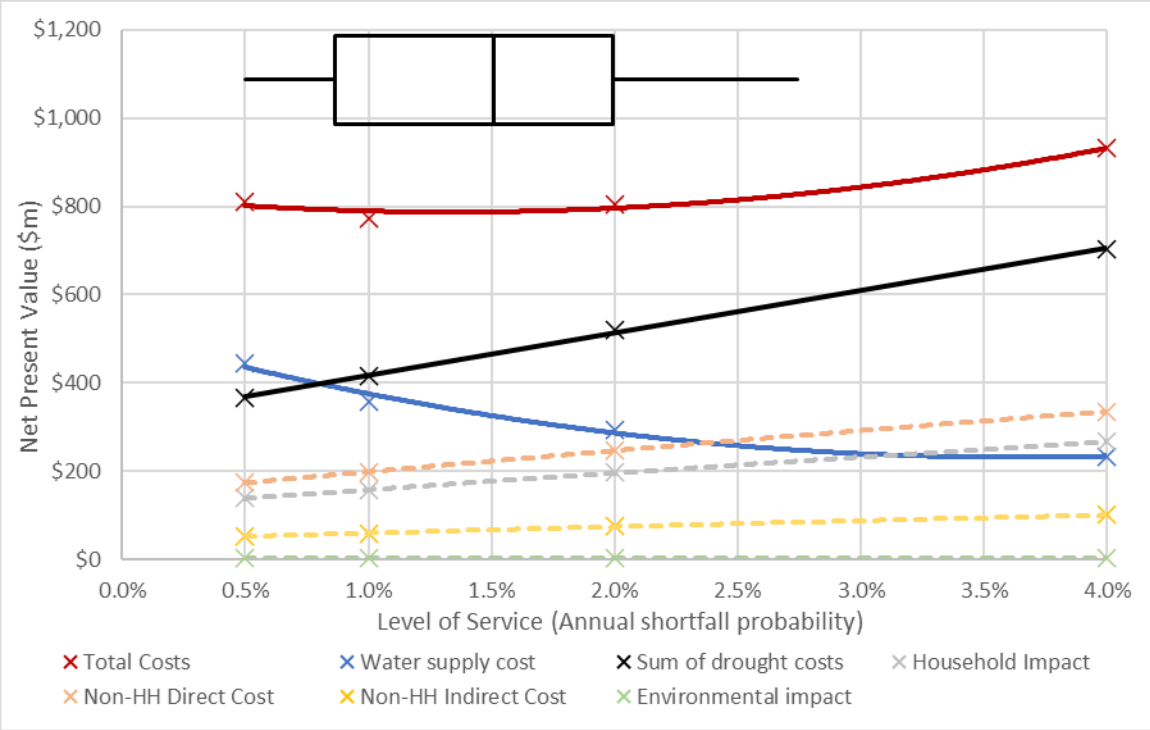


Figure 5: Results for emergency supply approach. Box and whisker plot of optimal level of service (minimum total cost) is overlaid

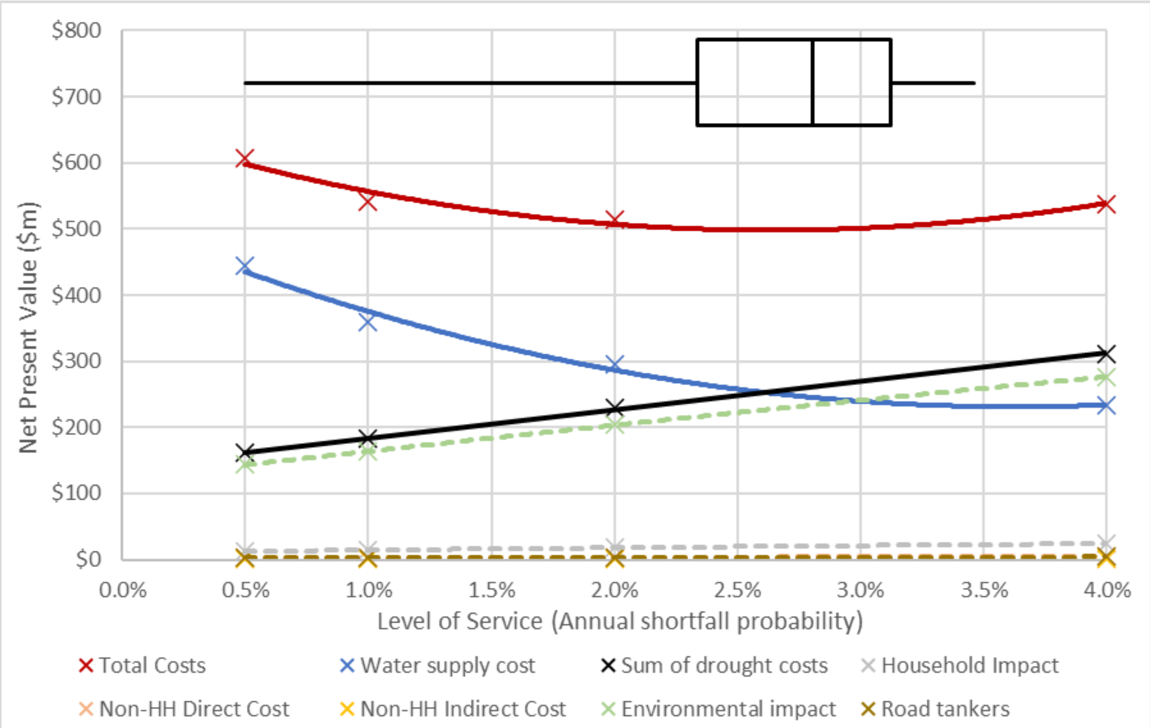
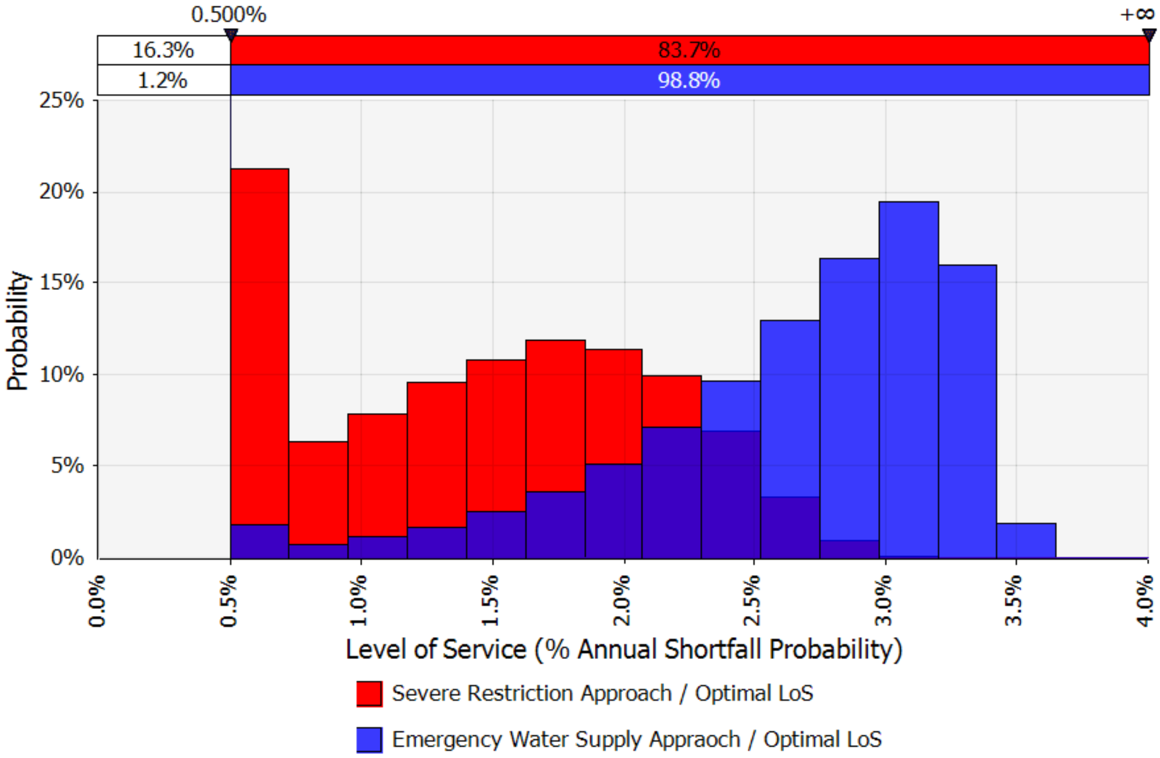


Figure 6: Optimal level of service results from Monte Carlo simulation for both severe restriction and emergency water supply approach



The results indicate:

- Taking water beyond environmental limits is likely to have a lower economic cost to applying severe restrictions where some customers' water is cut off
- Wellington Water's current 2%/1 in 50-year annual shortfall probability level of service sits within the range of optimal level of service results, albeit with some limitations and assumptions that need refining. This initial outcome was surprising in light of recent studies into the cost of drought in the United Kingdom either through considering severe restrictions, or through emergency water sources, have indicated the need for significantly improving up to a 0.2%/1 in 500 year level of service

Reasons for these results include:

- Drought costs are estimated per household per day. Wellington drought events will be short duration so of lower cost.
- A relatively low population and possibly higher capital costs than in the UK
- The true environmental costs may not be fully understood and captured.
- Reputation/political costs are not considered. These may be large, especially if a drought is perceived to be due to mismanagement.
- The emergency supply approach assumes no decrease in groundwater abstraction during a drought and that the flows in the Hutt River remain above the 1 in 100-year low flow level. These assumptions may be optimistic and the impact of climate change on these flows over the planning period was not considered.
- Uncertainties in Wellington Water's system modelling data are not considered.

- The benefits of improving LoS are not considered beyond drought risk. A higher LoS may allow less surface water abstraction resulting in environmental benefits, or may provide additional resilience benefits.

Sensitivity analysis indicated that the results are sensitive to the key inputs discussed in Section 3.2 and 3.3, as well as:

- Cost estimates for new water sources. The optimal level of service result is similarly sensitive to changes in Capex and Opex costs for new water sources as it is to changes in other key inputs such the cost per day of restriction for household or non-household users.
- Discount rate, as capital costs are paid upfront whereas the benefits of reduced drought risk accrue over time. The NZ treasury discount rate for water infrastructure of 5% was applied. An alternative 2% discount rate results in an optimal level of service at the lower bound of 0.5% for the severe restriction assumption, indicating an optimal level between 0% and 0.5%. The optimal level of service for the emergency supply assumption was 2.3%.

The aim of the study was to be comprehensive in assessing all types of drought costs however some costs such as the political or reputation impact of a drought were not considered. The results of this study can be seen as a lower bound. Considering these additional costs would encourage improving level of service further.

The cost of level 3 restrictions (such as outdoor watering restrictions) are low, and the additional environmental impacts from taking some additional flow from the Hutt River are low. Taking these measures early in a drought may be prudent to lower the risk of more severe household or environmental impacts.

4. CONCLUSIONS

The drought cost framework proposed in this study demonstrates a practical approach for integrating the range of different drought costs into water supply planning. Estimating the full range of drought costs can be used to identify the optimal level of drought resilience in a water supply system and help identify trade-offs between policy decisions during a drought. Expressing results in terms of economic costs allows for direct study of trade-offs.

The framework was successfully applied to a case study with Wellington Water. The results suggests an optimal level of service in the same range as their current policy, however further study is recommended to confirm the inputs.

Some key challenges and opportunities for further research were identified when applying the framework:

- There are a lack of primary New Zealand studies for estimating how much households are willing to pay to avoid water restrictions. Overseas studies can be applied with some uncertainty.
- Estimating the environmental costs of abstraction is difficult due to compounding layers of uncertainty. The impact of abstraction on environmental values is uncertain, as well as estimating the cost of these impacts.

Further study in these areas would give greater certainty into the optimal level of service of Wellington Water’s supply network. A study into household willingness to pay to avoid restrictions could be used by suppliers throughout New Zealand. The costs of these studies can be justified by the billions of dollars forecast to be spent on water infrastructure over the coming decades.

The trade-off between cutting off water to customers and severe environmental impacts from water takes is a difficult one. A drought in Wellington that forces this trade-off to be confronted is more likely than not in our lifetimes at current levels of service. Further study that improves our understanding of relative costs and community preferences will help suppliers make better informed decisions.

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