The Costs of Drought in Urban Water Supply Planning

George Beveridge

A thesis submitted in fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering, the University of Auckland, 2022. This thesis is for examination purposes only and is confidential to the examination process.

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 costs of increased water abstraction. It is therefore challenging to assess the full range of costs of a drought.

This research 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 study addresses some gaps in current research by focussing on drought costs in urban areas rather than agricultural areas, considering methods for estimating drought costs from both economics literature and water industry studies, and by providing practical guidance on how resulting drought costs can be integrated within water supply planning.

This paper applies the framework to Wellington Water, a New Zealand water supplier. 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 potentially high environmental costs. The results indicate that, in this case, taking water beyond environmental limits likely has lower economic costs than cutting off water. 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.

Acknowledgements

In submitting this thesis, I would like to extend special thanks to:

Wellington Water for providing data for the case study. Specifically, thanks to Geoff Williams and Julian Fyffe for taking the time to share their expertise on Wellington Water's network,

My supervisors Theunis F.P Henning, Asaad Y. Shamseldin and Kobus van Zyl,

My employer WSP for allowing me the opportunity to study,

And most of all, to my partner Eve for all her love and support.

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CHAPTER 1 INTRODUCTION

1.1 Background

Assessing the cost of drought is continuing to become 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 (Environment Agency, 2022). 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, as shown in Figure 1. Drought is the major cause of disruption to water supply networks in urban areas in developed countries. While preventing the impacts of drought occurring is a clear goal in water supply planning approaches, there is surprisingly little literature explicitly quantifying the cost of droughts and linking this to the cost of augmenting supply. Where it is quantified, there is not a consistent, practical framework in which drought costs are assessed.

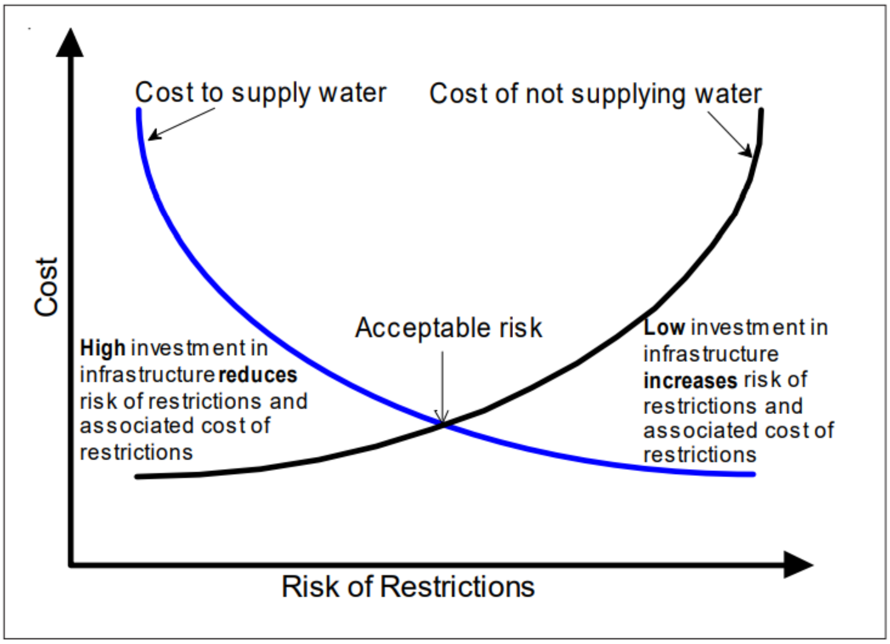


Figure 1. Trade-offs when setting water supply level of service objectives, from WSAA (2005)

1.2 Problem Statement

Water network planning decisions must account for the cost of future droughts. As such, suppliers seek to mitigate the effects of drought in their development of new water infrastructure. A supplier may for example choose to invest in increasing capacity of the network to avoid the impacts and costs associated with a drought event. Assessments of the cost of drought have been used to justify significant investment in water infrastructure in Australia and the United Kingdom (Cooper, Burton, & Crase, 2019; Metcalfe & Baker, 2011).

It follows that estimating the risk of droughts – and their cost – is a critical input for urban suppliers' investment decisions. The level of a supplier's investment in building new water infrastructure reflects its estimate of the cost of future droughts. A supplier may conclude that it is cheaper for it to improve network resilience now than face the costs of drought in the future. The estimate of drought cost is therefore a key variable which stands to influence investment decisions.

Despite its potential to have a huge impact on levels of investment in urban water supply infrastructure, the methods for estimating the cost of drought and integrating it into urban water supply planning are remarkably understudied.

Some gaps were identified in the literature assessing methods for estimating drought costs:

- Previous research has tended to focus on agricultural drought costs rather than drought costs in urban areas;
- Methods from economics literature are considered, however practical but less robust methods from water industry studies are not; and
- There is no guidance for suppliers on how methods for assessing drought costs would be integrated within their water supply planning.

The difficulty in quantifying the cost of drought helps to explain why it has not only received little academic attention but also largely remains to be implemented by suppliers (with little guidance).

Droughts have a range of direct costs to suppliers, businesses and industry as well as wider indirect and non-market costs to society. One of the major costs of drought in urban areas is the intangible, non-market value customers place on avoiding having severe restrictions imposed on their water supply which can be difficult to quantify. The indirect and non-market nature of certain drought costs complicate the ability to readily estimate the total cost of future drought events. Unlike other natural disasters, droughts do not generally cause damage to physical assets, and have minimal long-term impacts on the production capacity of an economy.

Estimating the costs of drought can also be useful for suppliers to balance the impact of when it is best to apply restrictions, such as applying earlier but less severe restrictions to avoid more costly restrictions. In a severe drought, a supplier may need to make difficult decisions between cutting off water supply to some customers and taking water beyond environmental limits, with high environmental and financial costs (Metcalfe & Baker, 2011; National Infrastructure Commission, 2018).

It is imperative that investment decisions for future water infrastructure are informed by accurate assessments of drought cost. Without robust methods for estimating the cost of drought, suppliers may over or underestimate its costs, distorting investments as a consequence. Network resilience may be insufficient (in the case of underestimate) or the investment of scarce resources should have been redirected (in the case of an overestimate of future drought cost).

Despite the challenges in estimating the cost of drought, it can have a substantial impact on levels of investment in water supply infrastructure, as demonstrated by the United Kingdom Environment Agency example. The Agency's decision was based on a study that took an avoided cost approach to estimating drought costs. The focus was the cost of supplying emergency water if a severe drought were to occur. This is a novel approach to estimating drought costs in urban areas – no other studies were found taking this approach to this extent.

1.3 Research Objectives:

The overall aim of this research is to improve decision-making in urban water supply planning by improving water suppliers' understanding of the cost of drought and ability to integrate such cost assessment within their water supply planning. Understanding the full cost of drought is essential for water suppliers to balance that potential cost against the significant costs of improving drought resilience and enhancing supply. Based on this aim, the following objectives are proposed:

1. Literature review of methods for assessing the cost of drought in urban areas, water supply planning methods and existing studies that have utilised drought costs to inform water supplier policy (Chapter 2);

2. Detailed assessment of methods for estimating drought costs in urban areas, reviewing methods from both economics and water industry sources (Chapter 4);

3. Develop a practical framework for a water supplier to integrate the different types of drought costs into water supply planning (Chapter 5); and

4. Apply the framework and a variety of methods for assessing drought costs in a case study with a New Zealand urban water supplier to gain insight into the practical challenges a water supply would face in integrating drought costs into their decision making. Test two different approaches a supplier may take during a severe drought, either cutting off water to some customers or taking

water beyond environmental limits, with high environmental costs (Chapter 6).

1.4 Scope

The focus of the research is assessing drought costs and integrating them into urban water supply planning in developed countries where the majority of customers are residential and businesses. The costs of agricultural drought are not considered. This scope is unique in the existing literature.

The focus of the research is on urban water suppliers. It follows that this research limits its consideration of options and decisions to those within the jurisdiction of such a supplier – that is to say, local drought mitigation policy rather than national policy.

The scope of this the review of water industry studies and guidelines limited to those from Australia, New Zealand, the United Kingdom and the United States. The scope was determined in part by accessibility of information in English and similarity in jurisdiction.

The cost of drought considers the direct, indirect and intangible costs of drought to society, not just those incurred by the water supplier. “Cost” refers to economic costs and considers environmental and wider social costs.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview

The costs of drought in water supply planning is a topic that intersects economics literature and water industry practice. A range of literature was reviewed from the perspective of an urban water supplier looking to integrate drought costs into its water supply policies. This chapter provides background to the following areas:

- Classification of drought costs in urban areas.
- Methods for assessing the costs of drought which are primarily from economics literature.
- Water supply planning practice of which a core focus is balancing the risk of drought with the costs of investing in water supply infrastructure. Conventional approaches to water supply planning and more advanced methods are reviewed.
- Existing studies that have attempted to integrate drought costs into water supply planning, from both economics literature and water industry practice.

As outlined below, the literature review identified two significant gaps: a lack of urban-specific assessment of drought costs and the absence of any integrated framework for assessing the full range of drought costs in water supply planning. The present study provides a unified framework to assist water suppliers to assess drought costs in urban areas and thus offers an important and practical contribution to the field.

2.2 Classification of Drought Costs in Urban Areas

There is no single standardised terminology for characterising the costs of droughts and there can be some overlap between cost categories. The most useful sources were a series of studies that summarised different methods for estimating different types of drought cost. (Ding, Hayes, & Widhalm, 2011; Freire-González et al., 2017a; Logar & van den Bergh, 2013; Meyer et al., 2013). "Cost" refers to the economic costs to society and should consider environmental and social costs/values.

There are three classifications of costs that are consistent in the literature that was reviewed. Minimising the number of classifications was considered preferable for simplicity. These are:

Direct costs of droughts are related to a reduction in water availability such as lost revenue for water utilities, reduced hydroelectric production, and business interruptions. The direct cost of reduced agricultural production likely to be less relevant for water utilities in urban areas. Droughts do not generally cause direct damage to physical assets the way other natural disasters do, with the exception of fires and damage to infrastructure due to subsidence (Logar & van den Bergh, 2013). Other types of direct drought costs include impacts on healthcare and the costs to water suppliers in sourcing emergency water, running water conservation campaigns and the lost revenue from supplying less water (Atkins, 2018).

Indirect costs are losses caused by the direct costs as they spread through the wider economy, usually later in time. For droughts these include unemployment, increased food prices and reduced tax revenue. Examples include the upstream impact on a farm's suppliers and the downstream impact on their customers if their production falls due to water scarcity.

Non-market costs or intangible costs are those that are difficult to measure in monetary terms and not tradeable in a market. Intangible costs related to droughts include environmental, health and social impacts. Environmental costs can include biodiversity loss, impacts on water quality as well as loss of recreational opportunities. Social costs include the welfare loss from water restrictions e.g. from water restrictions on filling swimming pools or watering gardens. It can be more difficult to evaluate the intangible costs of drought due to their gradual onset and the difficulty of separating naturally occurring drought impacts and those exacerbated by human activity (Markantonis, Meyer, & Schwarze, 2011).

There are other types of drought costs that were identified in some of the literature. These can generally be classified within the three types of costs above.

Business interruption costs are associated with the interrupted production from, for example, water scarcity during a drought (Meyer et al., 2013). Businesses interruption costs can safely be classified as either direct or indirect costs.

Risk mitigation costs were included in a study summarising method for estimating the costs of natural hazards by Meyer et al. (2013). The key costs affecting water utilities are the direct costs of planning, design, building and maintaining infrastructure. Risk mitigation costs can be classified into either the direct, indirect or intangible cost categories. The key point of separating risk mitigation costs as a separate category was to ensure they are not overlooked and because they may require different methods to assess.

Care needs to be taken when assessing risk mitigation costs as a counterfactual needs to be assessed to avoid double counting costs. i.e., preventative measures after all are designed to prevent some direct drought costs from being felt in the first place. Risk mitigation measures need to be assessed in conjunction with the expected event (in terms of magnitude, length) that the measure will be applied against (Freire-González et al., 2017a).

Any water supply infrastructure could theoretically be considered a risk mitigation cost as it reduces the risk of drought. However, limiting risk mitigation costs to only the direct, indirect or intangible emergency mitigation costs during a drought fits more appropriately into the water supply planning literature reviewed in the following Section 2.4, and is the approach adopted for this study.

Characteristics of Drought

Any assessment of drought costs needs to consider the unique characteristics of urban drought compared to other types of natural disasters, which are described by Freire-González et al. (2017a):

- Droughts do not generally cause direct damage to physical assets which is the main economic impact of most other disasters. This also means there is no post-event reconstruction period to consider.
- In developed countries droughts do not generally impact the long-term productive capacity of the economy, so this measure is not able to be used to assess drought impacts.
- The overall impact of a drought event is dependent on a combination of both its severity and its length and this relationship is not necessarily linear.
- The economic impact of a drought is very dependent on short term policy decisions such as the scale and timing of water restrictions and long-term policy decisions such as investment in water storage capacity.

2.3 Assessing the Costs of Drought in Urban Areas

2.3.1 Overview

Different methods are required to estimate the different types of drought costs discussed in Section 2.2. A variety of methods are required to estimate the full range of drought costs. There is no one single method that can be used to estimate all types of drought costs. This section primarily reviews economics literature and some water industry studies to identify methods for assessing the different types of drought costs.

2.3.2 Methods for Assessing Direct Drought Costs

Direct costs from drought are different from those of other natural disasters in that droughts do not generally cause physical damage to property (Freire-González et al., 2017a). Instead, direct costs are generally related to business disruptions caused by water scarcity, or direct costs incurred by a water supplier (Atkins, 2018; Meyer et al., 2013).

Direct costs can be assessed through **market valuation methods** which are based on directly observable market transactions. They are relatively easy to apply and fairly precise and are the method preferred by economists where suitable data is available (Logar & van den Bergh, 2013; Young, 2014)

The market valuation approach with the most studies specific to water utilities is the assessment of losses associated with drought adaptation measures, rather than costs of the drought damage itself. Examples from academic literature include Garcia-Valiñas (2006); Grafton and Ward (2008) and Martin-Ortega, González-Eguino, and Markandya (2012).

The water industry study by Atkins (2018) was the most comprehensive study found assessing drought adaptation measures, focusing on the costs of emergency water supply. Some emergency water supply methods such as trucking or shipping water can have costs assessed using market valuation techniques. Others such as the non-market environmental costs of abstracting water beyond environmental limits require different methods to assess (discussed in Section 2.3.4).

Assessment of GDP by sector is an approach to estimating direct drought costs by defining a relationship between a percentage decrease in water availability and a percentage decrease in GDP for a sector of the economy. Most previous studies have focussed on the impact of drought on agricultural production (Logar & van den Bergh, 2013).

There are some studies in literature that also focus on the impact of water shortages on retail and industrial sectors that are more relevant to urban water suppliers, however these were focussed on the impact of water disruptions from earthquakes rather than drought. Studies from Khater, Scawthorn, and Rojahn (1993); Chang, Svekla, and Shinozuka (2002) and Brozović, Sunding, and Zilberman (2007) estimate the proportional impacts of water shortages on GDP based on business survey data. Freire Gonzalez (2011) applied econometric techniques on government data with similar results. There was a general consensus that most sectors are resilient to small percentage reductions in water availability and to shorter duration shortages and less resilient to more severe reductions in availability and longer duration restrictions. However, there was not agreement on the exact relationship between water shortage severity and duration and GDP.

Outside of academic literature, the United Kingdom water industry studies by AECOM (2016) and Water UK (2016) link GVA (Gross Value Added, related to GDP) and water restrictions imposed by a water supplier during drought. The process is acknowledged as being a high-level approximation but offers a quick estimate of direct drought impact where more detailed data might not be available.

2.3.3 Methods for Assessing Indirect Drought Costs

Economics literature recommends **input-output (I-O)** or **computational general equilibrium (CGE)** methods as the most complete methods as they account for all sectors of the economy (Logar & van den Bergh, 2013; Meyer et al., 2013). However they do not account for non-market costs. I-O and CGE methods have large resource and data requirements.

Both I-O and CGE methods make use of I-O tables produced by government statistics offices that link inputs and outputs of each industry within the wider economy. I-O and CGE methods can estimate the wider impacts to the economy from a reduction in an input such as water. The advantage of I-O models is that they are easier to apply and are less data intensive than CGE models, however I-O models are restricted by the assumption there is no substitution between inputs which may result in costs being overestimated.(K. Jenkins, 2013; Meyer et al., 2013).

Studies that have used I-O modelling for estimating drought costs that included both agricultural and urban areas include J. Freire-González, C. A. Decker, and J. W. Hall (2017b); González (2011); (Martin-Ortega et al., 2012); Pagsuyoin and Santos (2021). Whereas CGE models related to drought costs have been mainly focused on agricultural drought costs (Nixon, Kaye-Blake, Morel, & Gämperle, 2021; Pauw, Thurlow, Bachu, & Van Seventer, 2011; Wittwer & Griffith, 2010).

There were no I-O or CGE studies focussing solely on the impact of drought or water restrictions in urban areas. No assessment was found commenting on the suitability of I-O or CGE methods in urban areas. Agricultural or industrial production has a much clearer link between water as an input and their respective outputs compared to office-based knowledge industries common in urban areas. There is an opportunity for further research to assess the suitability of I-O and CGE methods for assessing indirect urban drought costs.

The **economic amplification ratio (EAR)** is the ratio of the sum of total direct and indirect costs, to direct costs alone. For example, an EAR of 1.2 indicates indirect costs are 20% of direct costs. Applying an EAR to direct costs can be used to estimate indirect costs very quickly.

The United Kingdom water industry studies into drought costs from AECOM (2016) and Water UK (2016) discuss EAR but chose not to apply it. These studies also refer to data on GVA (Gross Value Added, related to GDP) multipliers by industry produced by United Kingdom Office for National Statistics (2018) that estimate indirect costs similarly to EAR. GVA multipliers have a similar restriction to I-O models in that they do not allow substitution between inputs so tend to overstate indirect cost. The GVA multipliers for office-based sectors were generally lower than for manufacturing or agricultural sectors.

There is an opportunity for further research to investigate into appropriate EARs for urban areas, especially for areas where office-based knowledge industries make up a large portion of GDP.

2.3.4 Methods for Assessing Non-market Drought Costs

The key non-market costs of interest to water suppliers are social costs including the welfare loss from water restrictions e.g. restrictions on swimming pools or watering gardens. A utility's policy decisions may also have non-market environmental costs such as biodiversity loss, loss of wetlands, impacts on water quality or well as loss of recreational opportunities (Meyer et al., 2013).

To incorporate the value of non-market/intangible costs into a cost benefit analysis, these costs first need to be quantified. Methods to assess non-market costs can generally be categorised into revealed preference methods and stated preference methods. Both use statistical methods to infer customers' willingness to pay (WTP) for a non-market good or service.

Revealed Preference Methods infer the willingness to pay for a non-market good by observing actual spending behaviour on related goods (Young, 2014). An example related to urban drought is the travel cost method which can be used to infer the value placed on recreational activities by how far people are willing to travel to get to the activity. Recreational activities such as kayaking or swimming could be affected by low river or stream levels caused by abstraction during a drought.

In comparison, **stated preference methods** rely on directly asking consumers the value they place on a real or hypothetical scenario. Stated preference methods are the most commonly used methods for estimating non-market drought costs (Ding et al., 2011; Young, 2014). In an urban drought context, stated preference methods have been used to estimate household's willingness to pay (WTP) to avoid water supply restrictions such as restricted garden watering or having water partially cut off.

Different studies produced their findings in different formats. UK studies by Metcalfe and Baker (2011) and Water UK (2016) focussed on WTP to avoid one day of different levels of water restriction. Australian studies by McNair and Ward (2012) and Hensher, Shore, and Train (2006a) expressed WTP in terms of a percentage reduction in the likelihood of a full year of water restrictions. Wilson et al. (2021) estimated volumetric and quarterly charges households would be willing to pay to ensure continuous supply with minimum restrictions – although the definition of minimum restrictions was not entirely clear.

There is an opportunity to review existing studies WTP to avoid water restrictions and the different formats they are presented in for how well they fit the conventional and modern water supply planning approaches discussed in Sections 2.4 and 2.5.

Stated preference methods are commonly used to quantify environmental values (Johnston, Rolfe, Rosenberger, & Brouwer, 2015). In an urban drought context, the most relevant environmental costs will be associated with people's WTP to avoid environment degradation from water abstraction.

A common theme mentioned in water industry studies was the difficulty in quantifying the environmental impact of directly linking water abstraction during drought with environmental costs (AECOM, 2016; Atkins, 2018; DEFRA, 2013; Water UK, 2016). There are multiple layers of uncertainty. The relationship between water supplier abstraction and environmental costs is complex and has does not appear well established. This may be partly attributable to the site-specific nature of abstraction from waterways making it difficult to create a single framework to apply.

The environmental costs of drought may be high. This is especially the case if a supplier chooses abstraction beyond environmental limits as an alternative to cutting off water to customers. If the environmental costs are underestimated, this could incentivise such abstraction with high environmental impacts. There is an opportunity for further research into a framework of linking abstraction and environmental costs more clearly.

Life satisfaction analysis asks people to assess their current levels of happiness as well as provide per capita income and other socioeconomic indicators that may impact the subjective level of happiness. Econometric modelling is then used to estimate an income equivalence change allowing the 'cost' of an individual's change in circumstance to be estimated (Logar & van den Bergh, 2013).

Only an Australian study by Carroll, Frijters, and Shields (2009) was found that applies this approach to the non-market welfare costs of drought. The results found a loss of welfare equivalent to A$18,000 for some drought events in rural areas. No loss of life satisfaction was identified for urban areas from drought conditions.

2.3.5 Assessing Drought Costs in Urban areas - Conclusion

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. Different types of costs require different methods to assess them, making it challenging to assess the full range of economic costs of a drought in urban areas.

There are summaries of the different drought cost methods from economics literature that are reasonably comprehensive and assess the types of data requirements and effort required for each method (Ding et al., 2011; Logar & van den Bergh, 2013; Meyer et al., 2013). There is a tilt towards agricultural costs in these reviews, possibility because this is where the bulk of previous studies focus.

There was some variation in methods for assessing drought costs in water industry studies compared to economics literature, generally with more of a focus on practicality over robustness.

There is a gap in the literature for a review of drought cost methods with a specific focus on urban drought costs. There is also an opportunity to integrate methods that originate from water industry studies as well those in current summaries that are from economics literature.

2.4 Water Supply Planning Practice – Long Term Planning

2.4.1 Overview

The purpose of a water supplier estimating drought costs is to inform decision-making. This could be in the form of long-term planning for water supply systems (this section) or for shorter term decision-making during a drought event (Section 2.5).

Long term water supply planning approaches were reviewed, both conventional and more modern approaches. One of the aims of this study is to integrate drought costs into water supply planning. This requires an understanding of different water supply planning approaches.

The term "conventional" approach is mentioned in the most recent UK Water Resource Planning guidelines but is not clearly defined in literature (Environment Agency, 2022). It refers to a balancing supply and demand based on a single or limited number of scenarios. The term "modern" approach is intended as an overarching term for a range of methods that have grown in popularity in recent decades, sometimes referred to as risk-based methods or simulation-based methods and have a strong focus on understanding uncertainty due to climate change.

The scope of this the review of water industry studies and guidelines to limited to those from Australia, New Zealand, the United Kingdom and the United States.

2.4.2 Conventional Approach to Water Supply Planning

In its simplest form, the conventional approach to water supply system planning is to estimate annual water demand and ensure that supply is able to meet this demand so as to avoid drought. The goal of the conventional approach is to supply sufficient water to meet the required demand for the least possible cost. The advantage of this approach is that it is simple to understand and to explain to the public. It has been used widely by water suppliers globally (Hall et al., 2020; Roach, Kapelan, Ledbetter, & Ledbetter, 2016).

The core principles of this approach were followed in the current or historical water supply planning guidance documents from Australia, New Zealand, the United Kingdom and the United States.

Water suppliers face a wide range of uncertainties in both supply (how much water the supplier can provide) and demand (from residential, business/industry and leakage). A range of possible uncertainties in water supply planning are shown in Table 1 from UKWIR (2002b).

Table 1. Sources of supply demand uncertainty outlined in UKWIR (2002b)

Supply side uncertainties	Demand side uncertainties
S1 Vulnerable surface water licences	D1 Accuracy of subcomponent data
S2 Vulnerable groundwater licences	D2 Demand forecast variation
S3 Time-limited licences	D3 Uncertainty of impact of climate change on demand
S4 Bulk imports	D4 Uncertain outcome from demand management measures
S5 Gradual pollution of sources (causing a reduction in abstraction)	
S6 Accuracy of supply-side data	
S7 Single source dominance	
S8 Uncertainty of impact of climate change on source yields	
S9 Uncertain output from new resource developments	

An approach to uncertainty proposed in the United Kingdom guidelines is to add a buffer to demand in the form of a headroom allowance (UKWIR, 2002b) and to supply in the form of an outage allowance (UKWIR, 1995). Headroom and outage allowances and are illustrated in Figure 2, showing how they effectively act as a factor of safety to ensure there is sufficient warning of a potential shortfall which is important given the long timeframes required to design, consent and develop new water supply sources. Deterministic and quasi-probabilistic methods are provided to estimate the headroom and outage allowances, considering the uncertainties shown in Table 1.

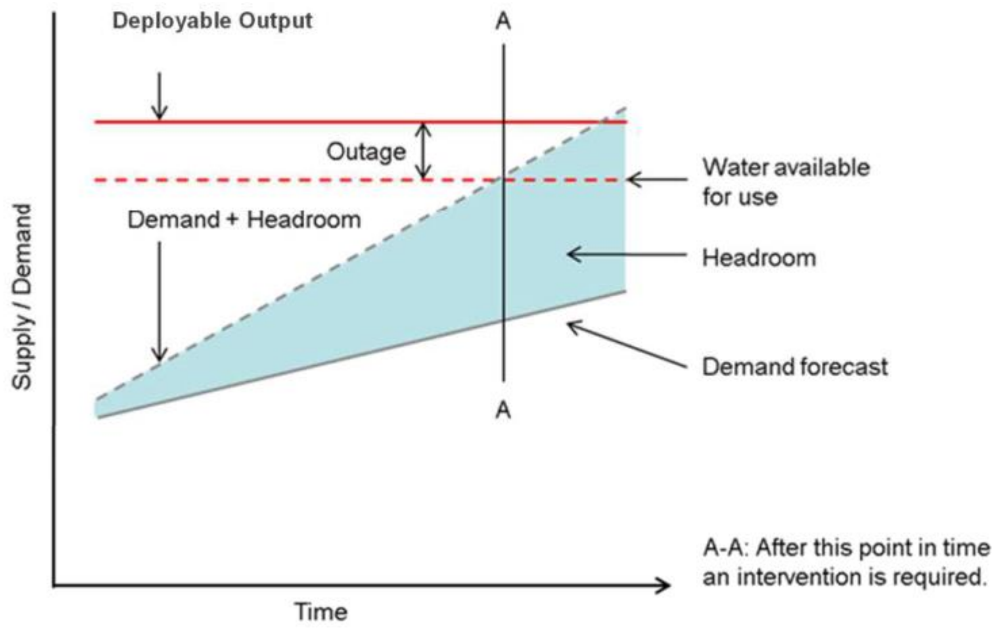


Figure 2. Illustration of headroom approach to water supply planning from Beca Limited and Tonkin + Taylor Limited (2020)

In the conventional water supply planning approach, there is a single set of baseline supply and demand forecasts which needs be based on a scenario with a set of assumptions behind it. The horizontal deployable output line in Figure 2 represents the level of continuous supply through a dry period derived from one set of possible supply assumptions. In reality, water supply output will not be consistent year to year if some or part of the supply is sourced from surface or groundwater.

Setting a target level of service (LoS) is a common approach to selecting a suitable water supply scenario, usually expressed in terms of a drought return period or terms of the worst recorded historical drought (Environment Agency, 2022; Hall et al., 2020). A worst historic drought may not suitably capture the risk of future droughts, especially in the face of climate change.

Setting a LoS based on a drought return period is more common. Current UK guidelines require water suppliers to plan to be "resilient to a 1 in 500 drought" which means there is a 0.2% annual chance of imposing emergency drought orders where the water to some customers is shut off. The most recent UK guidelines allows this headroom approach to uncertainty or more modern risk-based approaches discussed in Section 2.4.3 (Environment Agency, 2022).

The Australian WSAA (2005) water supply planning guidelines promotes a series of LoS targets for different stages of increasingly severe restrictions on water use, shown in Table 2. More recent Australian guidelines have moved away from the conventional approach and are discussed further in the modern approach in Section 2.4.3.

Table 2. Example level of service targets from WSAA (2005)

Stage of restriction	Annual frequency (no. of years per 100 years)	
	Current Level of Service	*Possible Future Level of Service*
One	10	20
Two	8	12
Three	4	4
Four	3	3

No national guidelines were found for New Zealand. Instead, suppliers apply suitable overseas methods. The two largest water suppliers in New Zealand, Watercare in Auckland and Wellington Water, both have adopted an approach similar to the conventional UK approach in UKWIR (2002b) (Beca Limited & Tonkin + Taylor Limited, 2020; Ernst & Young, 2020).

The American Water Works Association (2017) does not refer to target levels of service in its water supply planning guidelines. Instead "safe yield" is used which is the reliable withdrawal rate throughout a critical drought period. The method for calculating safe yield varies depending on the type of source but is conceptually similar to the UK headroom approach of allowing some allowing a form of buffer.

A WSAA (2014) review of water supply planning approaches found that the American cities of Santa Fe and San Francisco did not appear to target a specific LoS in their water supply planning process. The water supply planning approaches of other States or cities in the United States were not investigated.

A core assumption of conventional approaches to water supply planning is that expected rainfall operates under an uncertainty envelope that can be predicted based on records of past events. This assumption may have worked well in the past but may no longer be appropriate in the face of increased uncertainty, especially associated with climate change. (Milly et al., 2008).

2.4.3 Modern Approaches to Water Supply Planning

There is an acceptance in the literature that conventional methods for assessing water supply planning are becoming inadequate in the face of increasing uncertainty in both available supply and expected demand (Hall et al., 2020).

The primary driver of supply uncertainty in water supply systems is from anthropogenic climate change causing changes in rainfall, river flows and groundwater recharge rates (Roach et al., 2016). Another uncertainty comes from legislation that decreases the volumes of water that can be taken from existing sources due to environmental concerns, especially in areas where water takes are currently overallocated and unsustainable (Hall et al., 2020).

Demand for urban water supply systems is a function of population and demand per person. Both of these have significant uncertainty associated with them in the long term, with factors such as urbanisation, immigration and decreasing birth rates affecting population forecasts and a general trend of decreasing water use per person (Environment Agency, 2013b).

There are a variety of approaches to dealing with this uncertainty. The core of these approaches is setting up models that simulate how an entire water resources system will respond in the face of climate change. This includes considering hydrologic, socioeconomic and environmental impacts of a water management (Brown et al., 2015).

There are some key principles promoted by methods for assessing water systems under uncertainty (Borgomeo, 2022; Maier et al., 2016):

Flexibility – ability to change or adapt in the future depending on the outcomes that happen e.g. staging infrastructure so that capacity can be added over time if needed. Flexibility includes how quickly changes can be made and how quickly these can influence the system.

Robustness – ability to perform well under a range of possible future outcomes. This principle prefers options that have reasonably good performance in many scenarios, rather than one that works very well in some scenarios and poorly in others. To understand robustness, there is a need to model a wide range of possible future scenarios.

There are different measures for quantifying robustness, including *maximin* (least bad behaviour), *maximax* (best possible behaviour) *minimax regret* (minimise regret for the worst case) (Herman, Reed, Zeff, & Characklis, 2015). Borgomeo, Mortazavi-Naeini, Hall, and Guillod (2018) proposed the metric of measuring performance of an option in the absolute worst-case scenario that was modelled to reflect the risk-averse nature of urban water suppliers.

Addressing trade-offs – ability to assess trade-offs between multiple objectives. Water resources decisions often involve trade-offs between conflicting objectives for a supplier. Multi-objective optimisation methods are the key tools for assessing trade-offs, in contrast with traditional approaches where minimising costs is the main objective (Reed, Hadka, Herman, Kasprzyk, & Kollat, 2013).

The only study found that explicitly addressed the trade-off between levels drought risk (in terms of cost) and preferred level of robustness was a study by Borgomeo et al. (2018).

2.4.4 Water Supply Planning Conclusion

Modern approaches to water supply planning cover a much broader set of methods than conventional approaches. With all of the approaches, there is still a need for a counterfactual to justify choosing a certain level of service or level of investment. Avoiding the impacts of water shortages is clearly the goal for all the different planning approaches. Therefore, understanding and quantifying the costs of drought is a key input for any water supply planning.

It was noted by Borgomeo (2022) that the use of these modern approaches by water suppliers is less than might be expected given their ability to improve understanding of the risks facing water suppliers. Reasons suggested for the slow uptake included the conceptual challenges in applying these methods and difficulty in integrating them into existing processes.

It is notable that the UK, even after adopting more modern approaches to water supply planning, still recommends a set target LoS of a 1 in 500 year event (Environment Agency, 2022 #100). A possible reason for this is that drought cost studies may be seen as too resource intensive to complete at the supplier level and are better left to be decided at the national level.

Considering both conventional and more modern approaches should be a goal of a framework that aims to integrate drought costs into water supply planning due to the continued use of both approaches.

2.5 Water Supplier Policy – Drought Response

Water supplier drought response policies outline the steps a supplier will take during a drought such as restricting customers' water use or sourcing water from emergency sources. Drought response plans are linked to drought costs, as understanding the costs of different response options can inform which polices are selected.

Drought response guidelines were reviewed from Australia, New Zealand, the United Kingdom and the United States. The review focused mainly on industry guidelines rather than the plans proposed by individual water suppliers.

All of the policies reviewed followed a similar trend of establishing increasingly severe restrictions on water use as a drought becomes more severe. A typical example from the American Water Works Association (2011) is shown in Table 3 where reservoir storage level is the trigger to step up drought stages which represent ramping up to more severe restrictions on water use.

Table 3. Example of increasing level of water supply restrictions as a drought becomes more severe and storage levels decrease from American Water Works Association (2011)

Reservoir storage less than	Drought Stage	Water Use Reduction Goal
80%	Stage 1	10-15%
65%	Stage 2	15-25%
40%	Stage 3	25-40%
25%	Stage 4	40%+

The United Kingdom follows a similar progression of increasingly severe restriction levels. Lower-level restrictions begin with media campaigns to reduce water and voluntary reductions to water use. Mid-level restrictions include temporary bans of outdoor water use such as for watering gardens. Finally, the highest level of water restrictions represents cutting off water to some customers by rotation and emergency water abstraction (Environment Agency, 2022; Water UK, 2016).

Restriction levels in Australian guidelines follow a similar progression to the UK. Interestingly, the highest restriction levels do not suggest cutting off water to customers (Erlanger & Neal, 2005; Marsden Jacob Associates, 2022; WSAA, 2008). A possible reason for this is the difference is in Australia multi-year drought are more common whereas in the UK a dry period of 8-18 months would be expected to cause severe drought conditions (Water UK, 2016). Longer drought duration may give a supplier more time to plan, design and implement emergency water sources to prevent water being cut off to customers.

No national guidelines for drought response policy were found for New Zealand. The drought management plans for New Zealand's two largest suppliers, Watercare and Wellington Water, both followed a similar progression to overseas examples (Watercare, 2020; Wellington Water, 2022b).

The timing and severity of restrictions involves balancing the negative impacts of the restrictions that will reduce water use to avoid even more severe drought impacts in the future. A theme in all of the guidelines that were reviewed was the discussion on the importance of minimising drought impacts including economic, social and environmental impacts of drought. However, none of the guidelines that were reviewed provided a clear methodology of how to balance these costs and risks.

Restrictions and the cost of drought are linked in a framework from an economics perspective proposed by Freire-González et al. (2017a). The framework is illustrated in Figure 3 which shows how drought costs increase as a discrete step-change curve at the trigger levels where a supplier chooses to apply increased restriction levels (PD1, PD2, PD3). The cost of drought will only be felt once the policy decision to implement water restrictions is triggered (PD1). Dry periods that do result in water availability decreasing below PD1 will effectively have no impact on water supply in urban areas. Linking drought costs to restriction levels is a key insight to integrating drought costs into water supply planning and was also proposed in the industry studies by Water UK (2016), Borgomeo et al. (2018) and Marsden Jacob Associates (2022).

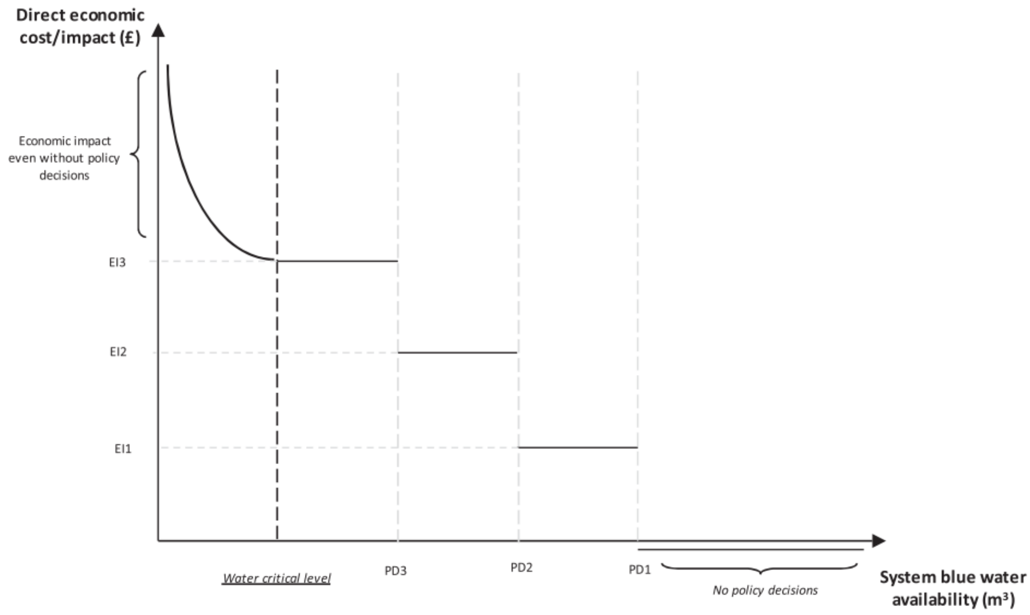


Figure 3. Economic impact curve of water supply policy in the short term

2.6 Integrating drought costs in water supply planning – previous studies

The principle of balancing the economic impacts of drought with the costs of improving water supply was expressed in the water supply planning literature that was reviewed. However, details on how the drought costs would be integrated into water supply planning in practice were lacking.

This section reviews water supply guidance documents and water industry studies that have integrated the costs of drought into water supply planning. There was a lack of studies that integrated drought costs into water supply planning in the literature. Studies were more likely to have been commissioned by water industry groups and produced by engineering or economics consultants. Few studies were found, however such studies would be expected to be more difficult to find and may not be publicly available compared to academic literature. Therefore, the range of industry studies discussed in this section are unlikely to be comprehensive.

Figure 1 from the WSAA (2005) Australian guidelines illustrate the trade-off between drought costs and water supply costs when setting a level of service target for water supply. The guidelines recognise the various types of drought costs such as on businesses or the intangible cost to customers of not be being able to water their garden.

A later Australia guidelines by WSAA (2008) utilised local studies into households willingness to pay to avoid water restrictions to estimate a customer demand curve as shown in Figure 4. Cost is per m^3.

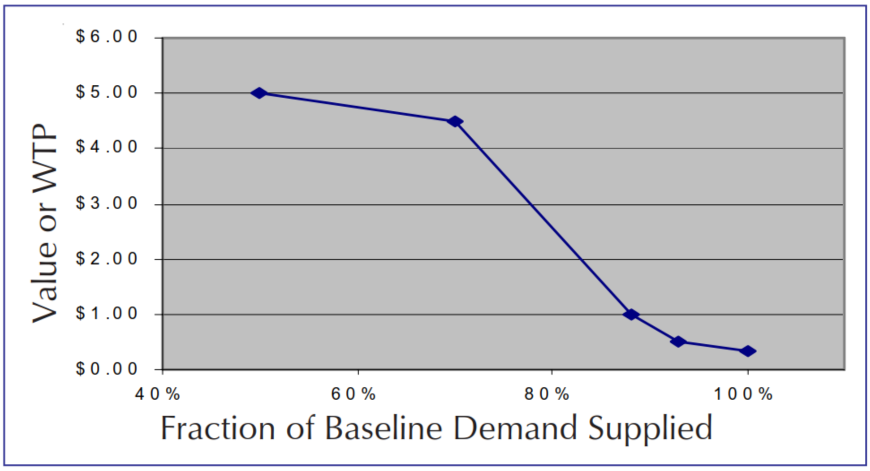


Figure 4. Demand curve for water supply to households from WSAA (2008). Cost is per m^3.

A demand curve such as this can be easily integrated into modelling of water supply options. The cost of water shortages can be estimated finding the fraction of baseline demand on the curve and multiplying by the total shortage volume in m^3. Over a planning period (in this case 25 years) the NPV can be estimated for total water shortage costs and total water supply costs in terms of capital and operation costs. The NPV of a range of 25 year water supply portfolios (various water supply options installed with different timings over planning period) can then be estimated to create a curve similar to Figure 1. The preferred portfolio can then be selected based on lowest notal NPV– represented by 'acceptable risk' in Figure 1.

A key limitation of the study is that the drought costs that are assessed are not comprehensive. Only the intangible costs of drought restrictions on households are assessed. Direct and indirect cost to businesses and environmental costs are not assessed. This leads to an underestimation of drought costs and a suboptimal level of service recommendation.

The other limitation that the demand curve may not reflect how suppliers will lower demand. Rather than a smooth curve, a supplier will apply a series of restrictions in discrete steps as discussed in Section 2.5 and shown in Figure 3.

A pair of UK studies commissioned by the water industry by Water UK (2016) and AECOM (2016) estimated the socioeconomic impacts of drought and integrated this into a wider study investigating water supply options. Both follow a similar approach in estimating both the direct costs to businesses and the intangible impacts of restrictions on households. They both approach the significant uncertainties involved in estimating costs over a 30+ year period through running different future climate and water investment scenarios as a sensitivity check.

The Water UK (2016) study appears a more useful example than the AECOM (2016) study as it explains in greater detail the logic behind each assumption. However one limitation of the Water UK (2016) study is that there the drought cost results are not publicly available, making it difficult to sense check the results and compare these to other studies. Another limitation is that some the key assumptions are not provided, such as the studies that were reviewed to estimate household WTP to avoid water restrictions.

Both the Water UK (2016) and AECOM (2016) studies discuss but do not consider the indirect costs from business water shortages. Both discuss the difficult of estimating the environmental impacts of increased water abstraction during a drought event. The AECOM (2016) study attempts to estimate environmental costs but the value may not account for the full range of environmental costs as they make up only 0.2% of total drought costs in the most severe drought scenario.

A study by Atkins (2018) took a different approach to the previous studies as it does not focus on the costs water supply restrictions have on customers. Instead, it assumes that it politically unpalatable to impose severe water restrictions that cut off water supply to some customers. Instead, it is assumed that governments and suppliers will do anything in their power to supply emergency water at high environmental and financial costs.

Emergency costs are expressed as £/megalitre/day in a marginal abatement cost curve (MACC) as shown in Figure 5. This approach allows straight forward integrating into water supply planning. The cost of any scenario can be read off the MACC by estimating the daily shortfall in megalitres as shown by the vertical lines Figure 5.

A limitation of a MACC is that it does not allow uncertainty in any of the emergency supply options to be expressed. This is especially challenging as many of the costs stem from the environmental impact of abstraction which is complex to estimate so an uncertainty band would be expected.

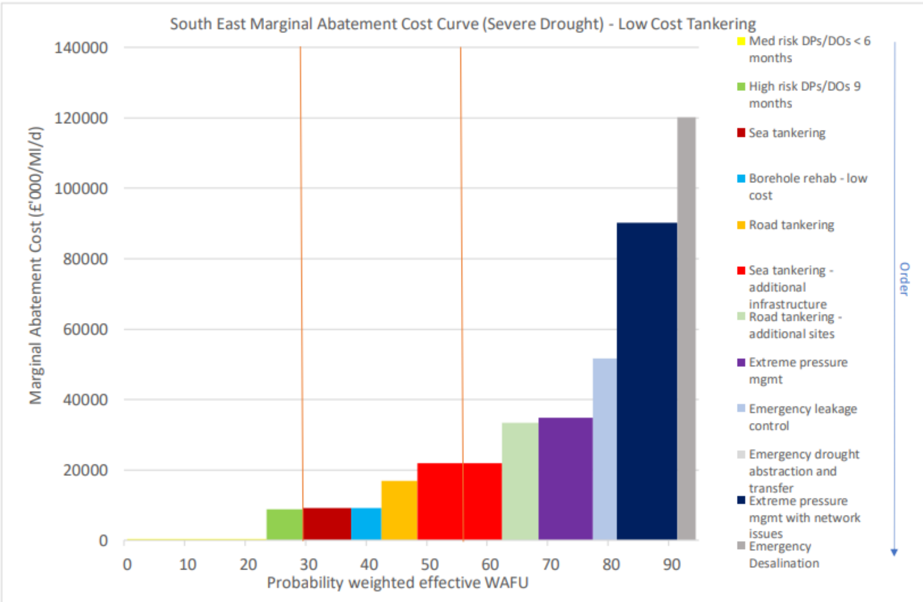


Figure 5. Example of a marginal abatement cost curve for emergency water supply (Atkins, 2018)

The Atkins (2018) study was utilised by UK National Infrastructure Commission (2018) to recommend significant improvements in levels of service targets required by water suppliers, including significant increases in investment in leakage reduction, demand reduction and new supply. These two studies were factors in the Environment Agency (2022) increasing the target level of service for water suppliers from 1 in 200 up to a 1 in 500 year level of service.

An example of a modern approach to water supply planning where drought costs have explicitly been considered is a study of London's water supply by Borgomeo et al. (2018). This study builds on the key idea of exploring the trade-off between drought costs and water supply costs shown in Figure 1 from WSAA (2005). Figure 6 shows the trade-off between drought costs and water supply costs (in the expected "average" future climate scenario) as well as the addition of a third variable of robustness. Each point represents a different water supply plan for the system over a 30-year planning period. Robustness is represented by the worst possible performance over 600 possible future climate scenarios for each water plan. The aim is to minimise all three variables of drought cost, water supply costs and robustness. The red dots illustrate that it is possible for robustness to be different for two water supply plans that have similar expected drought costs (restriction costs).The yellow dots were identified as the preferred balance between the three factors.

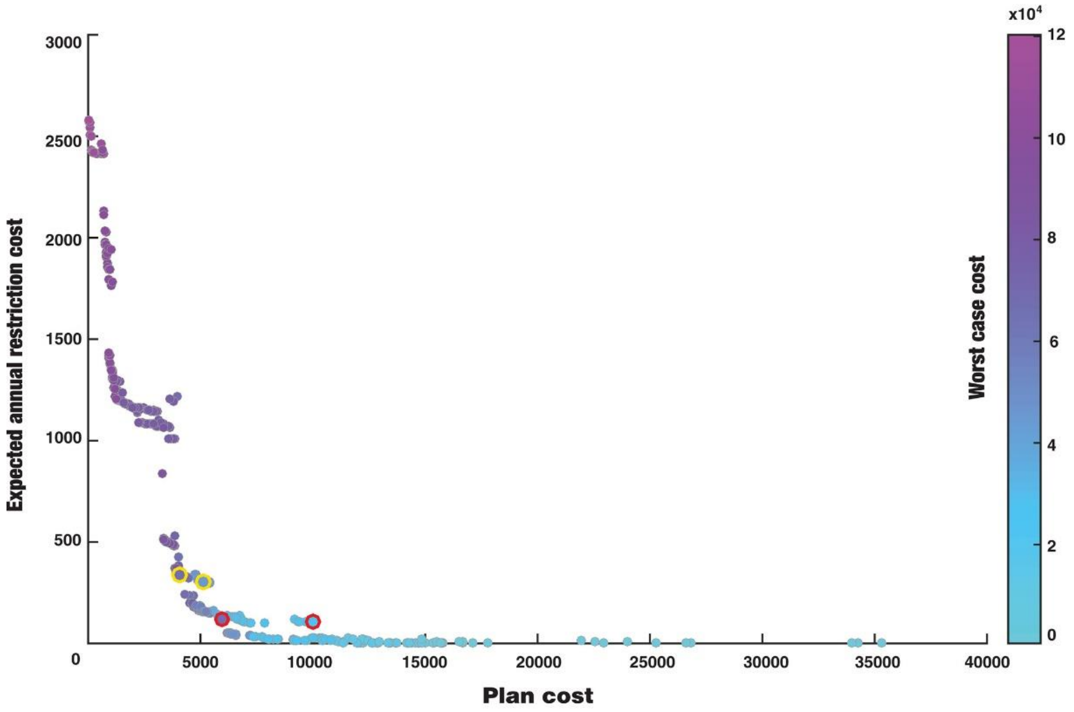


Figure 6. Trade-off between water supply cost (plan cost), drought costs (restriction cost) and robustness (worst case cost) from Borgomeo et al. (2018)

The key limitation of the study is that not all drought costs were considered – only an estimate of direct business costs and the intangible cost. If wider indirect and environmental costs were considered, drought/restriction costs would be higher and an option with a higher water supply plan cost may have been preferred. Representing robustness as performance in the absolute worst case is a relatively approximate representation but is a quick way to integrate robustness into modelling.

2.6.1 Conclusion - Integrating drought costs in water supply planning

A common gap in the studies that were assessed is that they were not comprehensive in assessing all drought costs. Environmental costs and business indirect costs were consistently not estimated in the studies that were assessed, most likely because they can be difficult to estimate. However, underestimating total drought costs results in recommending underinvestment in water supply. A conservative approximation of environmental costs and business indirect costs would be preferable to not estimating them at all.

The Atkins (2018) study assumed that severe water restrictions that cut off water supply are inconceivable and instead suppliers will supply emergency water at high financial and environmental costs. It is also the study that appears to have had the greatest policy impact, being part of the process that led to the UK increasing target levels of service from a 1 in 200 year to 1 in 500 year level. All the other studies focussed on customer WTP to avoid water restrictions. The most comprehensive study focussing on WTP was the study by Water UK (2016).

The various studies consistently took the approach of estimating total drought costs and total water supply costs, then comparing total costs over a planning period to recommend a policy option. There was no consistency in the types of drought costs that were estimated and how these costs were then into integrated into decision-making.

There is an opportunity to develop a unified framework for comprehensively estimating drought costs and integrating these costs into water supply planning, which is proposed in this study.

2.7 Conclusions from Literature Review

Four key studies emerged from the literature that most advance the topic of this research to integrate drought costs into water supply planning. Two of these studies are from economics literature and two are from water industry commissioned studies, reflecting the ethos of this research which is to integrate research and best practice from these two sectors. The present study is interdisciplinary, combining economics and civil engineering approaches to provide a practical framework for water suppliers . The following four studies form the foundation of this research.

- *Methods to assess costs of drought damages and policies for drought mitigation and adaptation: review and recommendations* by Logar and van den Bergh (2013) was the most comprehensive review of methods for assessing drought costs. It includes assessments of data requirements and effort required for each method. The focus is tilted towards agricultural drought losses than urban, partly as there has been more research in this area. Chapter 4 builds on this study by evaluating methods for assessing drought costs with a focus on urban drought and also including practical but potentially less robust methods that have been applied in the water industry.

- The study *The Economic Impacts of Droughts: A Framework for Analysis* by Freire-González et al. (2017a) identifies the unique features of drought in urban areas which need to be considered when assessing the costs of drought. The proposed framework is at a relatively high level and comes from an economics perspective rather than a water supplier perspective. Chapter 5 proposes a framework that is built on the principles of this study.

- *Water resources long term planning framework (2015-2065)* is a study commissioned by industry group Water UK (2016) which was the most comprehensive industry study into the different costs of drought and also the most complete example of applying drought costs to influence urban water supply policy. Methods for assessing drought costs in this study are discussed in Chapter 4 and the methodology of the study influenced the framework proposed in Chapter 5.

- *Analysis of the cost of emergency response options during a drought* by Atkins (2018) is a water industry commissioned study into the costs of drought. It takes a different approach than the Water UK (2016) in that it assumes that suppliers and governments will do anything possible to avoid cutting off water and will instead provide emergency supply at high financial and environmental costs. The emergency supply approach to estimating drought cost is discussed in Chapter 4 and is part of the framework in Chapter 5.

The literature review identified the following two significant gaps:

- An evaluation of methods for assessing drought costs that are specific to urban areas, with a focus on methods that are practical for waters suppliers to apply. This is explored in Chapter 4.

- A unified framework for integrating all types of drought costs into urban water supply planning. Previous studies have not considered all types of drought costs. A framework would need to consider the unique features of urban drought, be broad enough to integrate a range of types of drought costs and be able to fit within a range of water supply planning approaches. Such a framework is proposed in Chapter 5.

CHAPTER 3 METHODOLOGY

This section outlines the methodology of the present research. The goal of this research is to improve decision-making in water supply planning by improving water suppliers' understanding of the cost of drought. Three research objectives were defined based on this goal (see Section 1.3). Three objectives are proposed:

1. Detailed assessment of methods for estimating drought costs in urban areas, reviewing methods from both economics and water industry sources;

2. Develop a practical framework for a water supplier to integrate the different types of drought costs into water supply planning; and

3. Apply the framework and a variety of methods for assessing drought costs in a case study with a New Zealand urban water supplier to gain insight into the practical challenges a water supply would face in integrating drought costs into their decision-making.

3.1 Assessment of methods for estimating drought costs in urban areas – Chapter 4

Existing methods of estimating different drought costs in urban areas were assessed and compared in Chapter 4. There are a variety of types of drought costs in urban areas that may by their nature necessitate a supplier using a variety of methods to estimate total drought cost. This section first defines and discusses these various types of cost.

Methods for assessing drought costs were then assessed based on the following metrics:

- Effort and resources to apply the method relative to other methods assessing the same type of cost. This criterion considers the data requirements of the method and whether a supplier is likely to have this data available;

- Expected robustness – A measure of a method's reliability and repeatability; and

- Ease of integration within water supply planning and the framework cost of drought developed in Chapter 5. There is an assessment of the suitability of integrating the method within traditional and alternative water planning approaches.

There is a trade-off between robustness and the resources required to apply methods meaning there is not necessarily a single “best” method for assessing a type of drought cost. A supplier would be expected to choose methods based on their needs and their available data and resources.

3.2 Develop framework for integrating drought costs into water supply planning – Chapter 5

A framework for integrating drought costs into water supply planning was developed and the framework discussed in Chapter 5. Figure 7 illustrates the core idea of the framework which is to explore the trade-off in network planning and investment decisions: weighing up the relative costs of drought with the costs of enhancing water supply that might go unused.

Figure 7 also shows how a failure to consider all types of drought cost (for example, only intangible household costs), causes the optimal level of service to shift to the right, resulting in a lower optimal level of water supply investment.

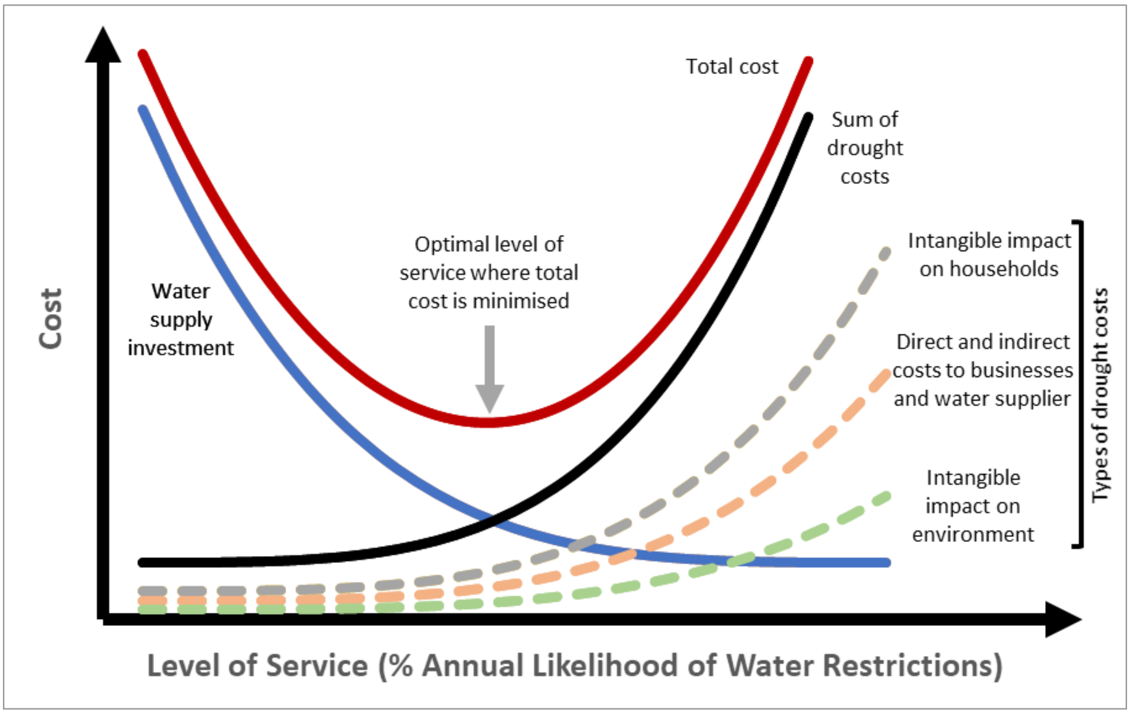


Figure 7. Trade-offs when selecting the optimal level of water supply investment

It is important that methods of assessing drought costs are compared within an appropriate framework. The key aims of the framework are to:

- provide a practical approach for a water supplier to integrate the cost of drought into its water supply planning;
- facilitate the application of the variety of different cost-estimation methods (assessed in Chapter 4);
- consider the unique features of droughts in urban areas and how these influence water suppliers' decisions in both the short term (single drought event) and the long term (long term water supply investment planning); and
- Allow integration into conventional approaches for water supply planning, where the primary aim is minimising total costs (shown in Figure 7), as well as more modern methods with a variety of objectives.

The framework was developed building on previous studies into drought costs from both economics literature and water industry practice.

3.3 Apply case study to New Zealand supplier – Chapter 6

This research applies the framework proposed in Chapter 5 and a selection of methods for estimating drought costs proposed in Chapter 4 to Wellington Water, a New Zealand water supplier.

The objectives of the case study were to test different methods to identify advantages and limitations and test the proposed cost of drought framework and to provide recommendations for future assessments of urban drought costs. The case study allowed methods and the framework to be applied to industry data, giving insight into practical challenges water suppliers may face assessing the cost of drought.

Time restrictions and data availability limited the number of methods identified in Chapter 4 that could be tested. In general, methods that require the least time and resources were applied.

Two different sets of assumptions to drought management were tested representing different approaches proposed in water industry studies:

- Severe restrictions approach where a supplier cuts off water to some customers during severe droughts; and
- Emergency water supply approach where a supplier goes to extreme lengths to avoid cutting off water supply to customers, with high financial and environmental costs.

The purpose of testing these different approaches was to improve understanding how drought costs can inform water supplier decision-making both during a single drought event and longer term water supply planning.

Finally, the results from the two different approaches were compared to Wellington Water's current level of service for drought resilience. A sensitivity analysis investigated which types of drought costs the optimal level of service is most sensitive to. This case study will help identify challenges and future research opportunities for a water supplier looking to assess and integrate the costs of drought into water supply planning.

CHAPTER 4 ASSESSMENT OF METHODS FOR ESTIMATING DROUGHT COSTS IN URBAN AREAS

4.1 Introduction

This chapter gives an overview of the types of drought costs likely to be experienced in urban areas. The varying nature of the costs requires different methods to estimate each type of cost. This section assesses each of these methods. In assessing each method, this research considers its robustness, the effort required for a supplier to apply the method, and the ease with which the method could be integrated into water supply planning. The assessment is from the perspective of a water supplier.

Chapter 5 proposed a framework for integrating these drought costs estimation methods within water supply planning. Finally, a selection of these methods were tested in a New Zealand case study in Chapter 6.

4.2 Types of Drought Cost

Drought impacts urban areas in multiple ways. This study aims to identify and quantify all impacts of drought as economic costs in monetary terms. Quantifying impacts in this way allows for direct study of trade-offs.

This paper divides drought into the following categories:

- **Direct costs** are those directly caused by a change in water supply that can be measured in monetary terms. Examples include lost production at a factory without water, reduced crop production from agriculture, or lost revenue for water suppliers due to supplying less water.

- **Indirect costs** capture the subsequent impacts of direct costs throughout the wider economy. Examples include the upstream and downstream impacts on a factory’s suppliers and customers, such as reduced production, higher unemployment or higher food prices.

- **Non-market costs** or intangible costs 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.

These three cost categories are consistently present in the literature reviewed. Other classifications proposed in the literature include business interruption costs and risk mitigation costs that can classified as direct costs.

Table 1 shows the range of drought costs for urban areas. Each of these costs can 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 4. Types of drought cost in urban areas

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, carbon emissions

	Direct	Public health costs from water shutdowns. Boil water orders, impact on healthcare facilities*
		Increased risk of fire from water shortages*
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 • unemployment
Water Supplier	Direct	Cost of emergency water to avoid severe emergency restrictions
		Loss of revenue from less water supplied
		Cost of restriction communication campaigns during restrictions
		Political fallout from drought. 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.

The following unique features need to be considered when identifying drought costs (Freire-González et al., 2017a).

- Droughts do not generally cause direct damage to physical assets which is the main economic impact of other natural disasters such as earthquakes or floods. This also means there no post event reconstruction period to consider.

- In developed countries, droughts do not generally impact the long-term productive capacity of the economy, so this measure is not able to be used to assess drought impacts.

4.3 Assessing Methods for Estimating Drought Costs

4.3.1 Challenges of estimating drought costs in urban areas

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

All types of drought costs need to be assessed for a comprehensive assessment of drought costs. Ignoring costs results in an underestimation of total drought cost.

Methods are categorised into those that assess direct costs, indirect costs and non-market costs. Some methods can be used to assess multiple types of costs. For example, a non-market valuation method may be suitable for assessing the impact of restrictions on households, as well as environmental costs. In this case, the method is discussed generally, and then assessed specifically in how it would be applied to assess each type of cost.

Previous summaries of the range of methods suitable for assessing drought costs include Ding et al. (2011); Logar and van den Bergh (2013); Meyer et al. (2013). Some gaps were identified in these approaches:

- There is a focus on economics literature. These summaries do not include a full range of methods for estimating drought costs that have been applied in water industry studies that may be less robust but are less resource intensive. Water suppliers have many competing demands for time and resources and may not be able to justify more robust methods. Having a wider variety of less robust but easier to apply methods would allow suppliers to get an indication of the scale of costs before committing resources to further study.

- Focus on agricultural drought costs as this is the area where most of the existing literature focuses. For example, Logar and van den Bergh (2013); Meyer et al. (2013) recommend Input-Output (I-O) and Computational methods (CGE) as the most complete methods as they account for all sectors of the economy. However, these methods do not estimate non-market costs which can be a significant portion of total cost in urban areas. These methods are discussed in Section 4.5 and may not be as suitable for assessing costs associated with urban droughts compared to agricultural droughts.

- Existing summaries do not focus on how well different methods would be integrated within urban water supply planning.

4.3.2 Process for selecting and applying suitable methods

1. Identify all costs that are relevant to the policy the supplier is investigating
2. Select one method for each relevant cost
3. Apply method
4. Produce the relevant input for the drought cost framework in Chapter 5

For the purposes of the framework the relevant costs are only those that arise as a result of a water supplier's actions and will vary within the policies being investigated. 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 suppler.

4.3.3 Criteria for Assessing Methods

This paper applies the following criteria to assess each cost estimation method:

- The effort and resources required for a supplier to apply the method, relative to other methods assessing the same type of cost. This criterion considers the data requirements of the method and whether a supplier is likely to have this data available. Rated low, medium or high.

- Expected robustness – Measure of a method's reliability. Resilience to a change in the type data used such as outliers. i.e. if the method was repeated with different data set, the results would be equivalent. Rated poor, reasonable or good.

- Ability to fit within existing drought water supply modelling approaches and within the cost of drought framework discussed in Chapter 5. Results that are specific and can be easily linked to water supply policy are preferable. For example, a method that estimates the cost per household per day of having no water, would be a preferred output as a supplier can model how many days they would expect this to occur under different policy options. Rated poor, reasonable or good.

The criteria are based on a similar assessment of drought cost methods undertaken by Logar and van den Bergh (2013). This study rated a range of drought assessment methods based on "expected precision" and "efforts and resources required". Robustness was considered a more appropriate criteria than precision as a measure of the performance of a method when used by a water supplier.

The present assessment focuses solely on drought in urban areas. This targeted assessment is a valuable contribution because previous drought studies, and previous reviews of studies, have focused primarily on agricultural losses and some losses in industrial areas. The assessment is based on a review of literature and practical application in water industry studies and resulted in some ratings being adjusted to better reflect the performance of methods in urban droughts.

Methods from water industry studies which were not present in Logar and van den Bergh (2013) were also assessed using the same criteria.

A selection of methods were tested in a case study in Chapter 6.

4.3.4 Table of Methods for Assessing Costs

Table 5. Summary of methods to assess the cost of drought for urban water suppliers. Source: own elaboration from Logar and van den Bergh (2013). Methods which are focussed only on agricultural drought costs are not included.

	Method	Types of drought costs assessed	Effort and data requirements (Low-medium-high)	Robustness (Poor-reasonable-good)	Integration into water supply planning (Poor-reasonable-good)	Types of data needed	Complementary methods	Section discussed
1	**Impact of water shortages on GDP per sector**	**Direct Costs** at industry level	**Low-medium** Data on regional GDP by sector should be readily available. The percentage impact on GDP per sector can be estimated based on previous studies or local business surveys.	**Poor-reasonable** Varies depending on source data. Previous studies are based on reviewing impacts of previous droughts, industry surveys, econometric analysis or professional judgement.	**Good** Output is in terms of % GDP loss per day per sector which can easily be integrated into water supply planning.	Share of GDP by industry/sector for relevant location. Review of previous studies that link droughts with percentage change in GDP by sector	Substitutable for method 2 where market data is not available.	4.4.3
2	**Market Valuation Techniques**	**Direct costs** for residential, business, agricultural or industrial users. Or for a supplier's emergency supply costs. Possible use to estimate welfare losses to consumers from restrictions - typically considered a **non-market cost**	**Medium** Some research is required to find suitable data to apply or to assist making reasonable assumptions Time consuming to apply across an entire economy	**Good** Valuation is based on observable market transactions	**Good** Output is in dollar terms However, there are limited types of drought costs that will have available data on observable market transactions.	Prices and quantities of relevant goods and services. Varies depending on technique.	Market valuation methods can be substitutes for each another.	4.4.2 for direct costs 4.6.5 for discussion on use for intangible costs to households

	Method	Types of drought costs assessed	Effort and data requirements (Low-medium-high)	Robustness (Poor-reasonable-good)	Integration into water supply planning (Poor-reasonable-good)	Types of data needed	Complementary methods	Section discussed
3	**Input-output analysis (I-O)**	**Primarily indirect costs** for business, agricultural or industrial users.	**Medium** I-O tables from government statistics office. Tables need to be regionalised. Direct costs are typically estimated using another method and need to be split by sector matching I-O tables.	**Reasonable-good** Depends on level of sector disaggregation. Tends to overstate indirect costs due to assuming there is no substitution between inputs.	**Moderate** Not as straight forward as other methods that can be directly inputs into water supply modelling. I-O model needs to be run for each scenario being investigated.	**Direct costs** that have been estimated using another method. Input–output tables from statistics office,	Substitutable for 4 Can use method 1 or 2 to inform direct costs	4.5.2
4	**Computational general equilibrium analysis (CGE)**	**Primarily indirect costs,** also **direct costs** from business, agricultural or industrial users.	**High** I-O tables from government statistics office. Tables need to be regionalised. Assumptions for linking water shortage and production losses. Additional data required for CGE over I-O includes trade matrices,	**Good** Depends on level of sector disaggregation More robust estimate of indirect costs than I-O method.	**Moderate** Not as straight forward as other methods that can be directly inputs into water supply modelling. Requires CGE model to be integrated into water supply modelling. Or CGE model to be run for each scenario being investigated	Input–output tables from statistics office, assumptions for linking water shortage and production losses.	Substitutable for 3	4.4.3

	Method	Types of drought costs assessed	Effort and data requirements (Low-medium-high)	Robustness (Poor-reasonable-good)	Integration into water supply planning (Poor-reasonable-good)	Types of data needed	Complementary methods	Section discussed
5	**Economic Amplification Ratio**	**Indirect costs** from business, agricultural or industrial users.	**Low** Based on review of previous studies I-O, CGE and GVA multipliers.	**Poor-reasonable** There are few previous studies assessing indirect costs in urban areas. However, EAR appears to be a reasonable approximation.	**Good** Simple multiplier can easily be applied to direct costs to estimate the indirect costs.	Estimates of EAR from I-O, CGE methods. Or from GVA multipliers. Information on the types of industries in the area.	Substitutable for method 3 or 4	4.5.4
6	**Stated Preference Methods** Contingent valuation or choice experiments	**Intangible costs** to households from restrictions or environmental impacts Has also been used to estimate costs typically considered **direct costs**	**High** An original stated preference study is time and resource intensive to complete.	**Reasonable-Good** Contingent valuation – reasonable Choice experiments – good Stated preference may be the only practical methods of estimating some intangible costs.	**Good** An original study can be designed so that the results format allows easy integration into water supply modelling. Ease of integrating environmental costs depends on existing studies into relevant waterways.	Survey of stated willingness to pay demographic and socio-economic data, preferences, Existing studies into environmental conditions and impacts of abstraction in relevant waterways.	Some types of costs may be substitutable for method 7	4.6.2 for intangible costs 4.4.4 for possible use estimating direct costs
7	**Revealed preference methods**	**Intangible costs** of recreational impacts. Very limited application for the types of urban drought costs compared to stated preference methods	**Medium-High** An original revealed preference study is time and resource intensive to complete.	**Reasonable-Good** Revealed preference may be the only practical methods of estimating some intangible costs.	**Good** An original study can be designed so that the results format allows easy integration into water supply modelling.	Survey of travel times and costs associated with recreation in area of interest	Some types of costs may be substitutable for method 6	4.6.3

	Method	Types of drought costs assessed	Effort and data requirements (Low-medium-high)	Robustness (Poor-reasonable-good)	Integration into water supply planning (Poor-reasonable-good)	Types of data needed	Complementary methods	Section discussed
8	**Benefit or Value Transfer** Aggregation or transfer of previous original studies	**Intangible costs** to households from restrictions or environmental impacts Can be used to transfer **direct costs** where previous studies are available.	**Medium** Resources and expertise are required to review suitable previous studies and adjust for similarities and differences between locations.	**Reasonable** Depends on the availability, similarity, and quality of previous studies.	**Reasonable-Good** Depends on the format of results of previous studies. Some studies may not be usable due to the format of their results.	Suitable relevant stated preference of revealed preference studies.	Substitutable for stated or revealed preference methods 7 or 8.	4.6.4

4.4 Methods for Assessing Direct Costs

4.4.1 Introduction

As mentioned in Section 4.2, a unique feature of drought compared to other natural disasters such as earthquakes or floods is that drought does not generally cause direct damage to physical assets. Instead, the direct impacts of drought are generally related to the disruption of water supply.

This section assesses methods for estimating the cost of these direct impacts based on the criteria outlined in Section 4.3.3. Note that the focus on this study is estimating costs of future hypothetical drought to support water supply planning decision making. Estimating costs from past droughts is useful for a water supplier, but only to assist estimation of future drought costs. The section assesses the following four methods:

- Impact of water shortages on GDP per sector;
- Market valuation techniques; and
- Stated preference methods

The application of these methods to assess specific drought costs is discussed in this section.

A challenge in estimating direct costs of drought with any method is that one must first understand the exact mechanism of water disruption. As discussed in the drought cost framework in Chapter 5, the impact of drought in urban areas is heavily dependent on suppliers' policy decisions in applying water restrictions. For example, a supplier could restrict water to certain industries but not others, or to residential users but not to businesses, or completely shut off supply to certain sections of the network by rotation.

The impact on a business will be different from having water cut off every second day compared to being forced to reduce demand by 50%. Both may result in the same 50% water savings.

There may be spatial differences where a supplier applies water restrictions. Technical limitations of a supply network may mean some sections will be cut off before others.

A supplier may need to apply spatial analysis to adjust costs, focusing on the area and the types of customers that will be most affected. However, for the purposes of the framework it was assumed that a supplier applies restriction to each sector consistently throughout a network. For example, retail businesses are assumed to be restricted consistently no matter their location.

4.4.2 Impact of water shortages on GDP per sector

This method is based on estimating a percentage decrease in GDP caused by drought, broken down by sector of the local economy. Disruption to an urban area's water supply caused by drought can have severe impacts but certain sectors of the economy will be more resilient to water disruptions than others. For example, retail activities would be expected to be impacted less than food manufacturing.

This method was not included in summaries of methods for assessing drought costs from economics literature (Ding et al., 2011; Logar & van den Bergh, 2013; Meyer et al., 2013) but was applied in some water industry studies (AECOM, 2016; Water UK, 2016).

This method is described in detail in this section as no other description of the method and how it could be integrated into water supply planning was found in the literature.

This section investigates the challenges of integrating GDP per sector method into water supply planning, discusses aggregate production functions which are an alternative approach to the method and discusses two UK water industry examples of the applying the method.

4.4.2.1 Challenges in integrating GDP per sector method into water supply planning

The following challenges were identified in integrating the GDP per sector method into urban water supply planning:

- The proportional water shortages from water restrictions;
- The impact of partial water disruptions;
- Drought duration;

- Linkage to indirect cost methods; and
- Changes Over Planning Period such as an increased number of people working from home.

Proportional water shortages from water restrictions

As discussed in the framework in Section 5.4, costs should be linked to the restrictions a supplier plans to impose in its drought management plan. A plan should clearly outline how restrictions will be applied and how specific sectors will be impacted in terms of a proportional shortage of water.

Industry studies from the United Kingdom including Water UK (2016), AECOM (2016) and DEFRA (2013) link losses to the local levels of water restrictions on a 1-4 scale. The most severe Level 4 restrictions assume rotating water cuts to the network. However, it is not made clear in any of these studies what percentage reduction in water supply this assumes.

For this approach to work, there needs to be a clear understanding of how each sector is affected by each level of water supply restriction. Care needs to be taken in transferring values from these studies to other locations as the impact of each restriction level would need to be comparable in both the original study and the location of interest.

Partial disruption to water supply

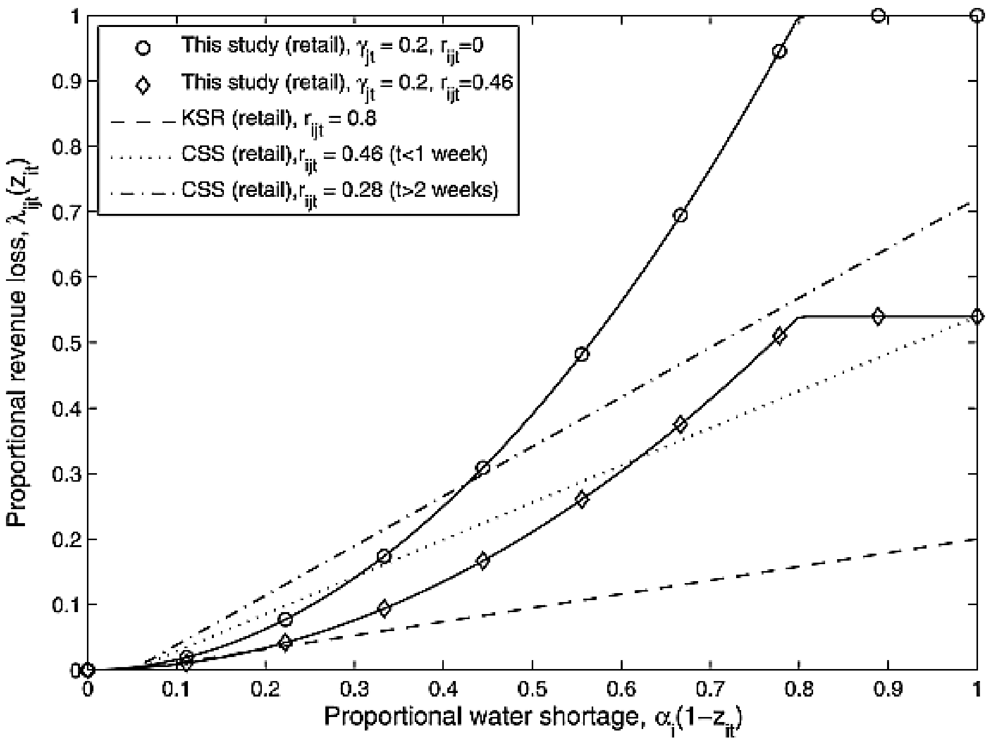
The direct impacts of drought are complicated by a lack of certainty on how much water will be restricted. Water disruption caused by an earthquake may shut off water entirely until it can be service is restored. Whereas during a drought a supplier may apply measures to reduce demand voluntarily or rotate through cutting off sections of the network rather than shutting off water entirely.

Completely shutting off water supply will necessarily impact a business. However, the impact of a partial disruption to a business's output is less certain. The impact of partial disruption is important to understand as during a drought a supplier is likely to apply partial restrictions on water use, at least at the beginning of a drought event.

There are many possible ways a partial disruption could occur. A 50% disruption to water supply could involve having water shut off on alternate days, 50% of an industry being completely shut off while the remainder being unaffected, or it could mean all of industry must reduce their daily water use by 50%. All of these will have different impacts. It is not always clear which of these assumptions has been applied in studies that estimate the impact of partial water disruption.

Figure 8 shows productivity loss curves from three studies, comparing revenue losses with the percentage of water shortage. Shortages can be either to individual businesses or to industry sectors.

Figure 8. Retail productivity loss curves from Brozović et al. (2007)



Khater et al. (1993) (KSR) and Chang et al. (2002) (CSS) estimate that up to a small, 5% decrease in water availability will not impact output at all. Losses will then increase linearly with the percentage water shortfall from normal levels. These results are from a survey of businesses following earthquakes in California. Brozović et al. (2007) (labelled this study) applies similar assumptions but with increasing marginal losses as water disruption increases.

Relationship between drought duration and direct costs

Direct costs may not increase linearly with time. Businesses may be able to cope with short duration drought, but struggle with longer duration events.

A linear relationship between the impact of water disruptions and duration was assumed in some studies, at least in relatively short duration events (Khater et al., 1993; Water UK, 2016). Others assume a linear relationship for relatively short duration events, then costs increasing over time as shown in Figure 9 (Chang et al., 2002).

Figure 9. Resiliency factors (% output under a total water outage) for a variety of industries from Chang et al. (2002)

Industry	Water-outage duration		
	<1 week	1–2 weeks	⩾ 2 weeks
Agriculture	0.53	0.35	0.30
Mining	0.73	0.48	0.44
Construction	0.68	0.47	0.43
Nondurable manufacturing	0.42	0.34	0.28
Durable manufacturing	0.42	0.34	0.28
Transportation	0.65	0.49	0.43
Communication/utilities	0.65	0.49	0.43
Wholesale trade	0.51	0.36	0.30
Retail trade	0.46	0.32	0.28
FIRE	0.44	0.27	0.24
Business/repair services	0.45	0.33	0.27
Personal services	0.45	0.33	0.27
Entertainment services	0.45	0.33	0.27
Health services	0.27	0.21	0.19
Educational services	0.45	0.33	0.27
Other services	0.45	0.33	0.27

Linkage to Indirect Cost Methods

Some indirect cost estimation methods rely on government statistics that aggregate the economy into sectors. Matching the sector or industry categories to these government classifications will assist if these indirect methods are to be applied after direct costs are estimated.

Changes Over Planning Period

A typical planning period for a water supplier is in the order of 20-50 years. The proportional GDP by sector could be very different by the end of the planning period.

There are few long term growth forecasts that are broken down by sector or industry, making this difficult to estimate (Water UK, 2016). In the absence of data, it is reasonable to assume that proportional GDP by sector will remain constant.

Areas where the makeup of sectors is rapidly changing, such as a trend of deindustrialisation, are likely to see the greatest impact. Shifts from one office-based knowledge to another are unlikely to significantly change the proportional impact of drought on GDP.

Impact of Working from Home

Urban areas in developed countries have a large portion of their GDP driven by 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 where working from home is much more common and streamlined after the COVID-19 pandemic, the impact of short duration shutdowns on non-households may have been overestimated.

If water disruptions force offices to close, people will be stuck at home. Water disruptions will still affect homes and would certainly still reduce capacity to work. For example, time may need to be spent each day fetching bottled water or filling containers from some central location. But overall, there could still be a significant reduction in the direct costs of droughts in urban areas. This would be an interesting topic for further research.

4.4.2.2 Aggregate Production Function

Freire Gonzalez (2011) linked sector GDP with water losses through an aggregate production function. Y_{it}, the total output of sector *i* in period *t* is a function of water consumption *W* and the output elasticity of water γ, as well as other factors that contribute to output.

$$Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta} W_{it}^{\gamma} \tag{1}$$

Equation 1, if displayed graphically, would show a relationship between output and water availability is similar to the curve labelled ‘this study’ in Figure 8 with increasing marginal impacts. A small decrease in water availability will result in a small decrease in output, with larger water disruptions having a much larger impact.

The output elasticity of water for five economic sectors were estimated in Freire Gonzalez (2011) as shown in Table 6. This was estimated using econometric methods and data from the National Statistics Institute of Spain and other Spanish government sources.

Table 6. Output elasticity of water for five sectors from Freire Gonzalez (2011)

Aggregated economic sector	Estimated elasticity
Agriculture	0.16
Extractive industries	0.08
Manufacturing industries	0.26
Market services	0.28
Non-market services	0.24

A similar approach was applied by Rose and Liao (2005) but with 20 economic sectors considered. Production functions were integrated into a Computation general equilibrium model, as discussed in Section 4.5.3.

A development in this study is accounting for adaptive behaviour of businesses during a short term water disruption, based on the assumption that managers will be able to act urgently to adapt practices to reduce non-essential water use.

This approach is an improvement on approaches such as surveying local businesses or professional judgement. However, this approach appears more suitable for sectors such as agriculture and manufacturing where water is a clear input into a production output. For urban areas where there are a diverse range of sectors, such as retail or office-based work, the impact is more difficult to determine.

Production functions could also be classified under market valuation methods.

4.4.2.3 UK Water Industry Study Examples

Industry studies from the UK linked GDP losses by sector to water restriction levels. The basis of this relationship was based on reviewing historical droughts and professional judgement.

The Water UK (2016) values in Figure 10 were based on reviewing data from historical droughts of 1976 in the Thames are and 1995/96 in Yorkshire. They estimated these values are accurate ±50%.

Figure 10. Losses per public water supply (PWS) restriction level for a selection of sectors from Water UK (2016)

Industry			PWS S2	PWS S3	PWS S4
Agriculture, forestry and fishing	Rain-fed agriculture	Cereals	N/A	N/A	N/A
		Potatoes rain-fed	N/A	N/A	N/A
		Other rain-fed crops	N/A	N/A	N/A
	Irrigated crops	Potatoes irrigated	N/A	N/A	N/A
		Strawberries	0%	100%	100%
		Other irrigated crops	N/A	N/A	N/A
	Livestock	Livestock	0%	0%	25%
Wholesale and retail trade; repair of motor vehicles	Retail sale of flowers, plants, seeds, fertilizers, etc.		0%	30%	30%
	Other wholesale and retail		0%	0%	25%
Administrative and support services	Landscape service activities		25%	100%	100%
	Other administrative and support services		0%	0%	25%
Arts, entertainment and recreation	Sports activities		50%	50%	50%
	Other arts and entertainment		0%	0%	25%
Manufacturing	Food products, beverages and tobacco		1%	10%	75%
	Textiles, wearing apparel and leather products		1%	10%	75%
	Wood and paper products and printing		0%	0%	50%
	Coke and refined petroleum products		0%	0%	50%
	Chemicals and chemical products		1%	10%	75%

The basis of the losses by sector applied in AECOM (2016) are from a combination of consultation with businesses and professional judgement.

DEFRA (2013) assesses losses in the 2011/12 drought in England and goes into the highest level of detail of the studies reviewed, breaking down the impact on affected sectors such as agriculture, retail nurseries and golf courses. An issue raised in this study is that the 2011/12 drought was not severe enough to apply the highest level of water restrictions, so the impact of these could not be assessed. The challenge of estimating future drought impacts based on historical drought costs is that the costs of greatest interest are those from extremely severe droughts, and these may not have occurred in the recent past.

4.4.2.4 Conclusion

The basis of the values for percentage losses in GDP per sector applied in the studies reviewed were surprising lacking in detailed studies to support them. Losses were estimated through surveys of local businesses or through reviewing previous drought costs. Severe water restrictions may never have been applied before in an area.

There has been more research into the impact of drought on agricultural and manufacturing losses. It is much more straight forward to link agricultural and manufacturing losses to GDP losses as water is a direct input in production. Urban areas have a much more diverse range of sectors such as retail, construction, health and office based sectors. Good data was not found linking water losses to these sectors with the impact of a future hypothetical drought.

It can be difficult to directly compare studies as they are made with different assumptions, especially industry studies that are linked to the severity of local restrictions that may vary between locations.

The challenge of change over the 20-50 year planning period was explored. The make-up of an economy can change significantly over this period, or there could be changes in how people work, such as the rise of working from home. Both of these could influence values.

The GDP per sector method has relatively poor robustness with low resource and data requirements. Water UK (2016) suggests a ±50% level of uncertainty is appropriate when applying this method. The aggregate production function approach proposed by Freire Gonzalez (2011) is a way of improving robustness with greater resource and data requirements.

4.4.3 Market Valuation Methods

4.4.3.1 Overview

Market valuation methods covers a broad range of valuation approaches that involve observing market transactions. This is preferred method for estimating direct drought costs where possible (Logar & van den Bergh, 2013). Where market valuation methods are expected to have high robustness where they are able to be applied.

There are a limited drought cost types that can be estimated using market valuation techniques.

- Avoided costs (direct emergency supply costs)
- Replacement or repair costs

The use of market techniques is limited in estimating drought costs. It is more likely to be used to estimate cost of drought adaptation measures (such as emergency supply costs) than for the impacts of drought itself (Logar & van den Bergh, 2013). Reasons for this include:

- Droughts do not generally cause direct damage to physical assets so there are no replacement or repair costs to estimates

- The price that water supplier's charge customers generally does the true value of water, so volumetric water losses are not suitable value of drought losses. Suppliers focused on full cost recovery rather than at its marginal cost,

This section discusses the types of costs that are able to be estimated with market valuation methods and integrated into water supply planning.

4.4.3.2 Water supplier costs

There are a variety of direct costs to the water supplier that have market prices so can be estimated through market valuation. Water supplier costs include:

- Lost revenue from reduced water use during drought restrictions. These costs can be estimated my multiplying volumetric charges with the estimated reduction in water use. There may also be lower revenue from lower wastewater use if this is also charged for.

- Fines from regulators for abstraction beyond environmental limits or for not meeting level of service targets.

- Costs of emergency water supply such as from trucking or shipping water.

- Cost of fast tracking capital projects would not have been otherwise be done.

- Cost of communication campaigns.

4.4.3.3 Avoided cost - Cost of Emergency Supply

The cost of drought can be avoided if sufficient emergency water can be sourced to avoid the drought's impacts. The methods for sourcing emergency water will differ by location. Some methods include trucking or shipping water, or abstraction from surface or groundwater beyond environmental limits.

Some emergency supply costs have direct costs that can be estimating through market methods, such as trucking or shipping water. Others such as abstraction beyond environmental limits will have some direct cost but also significant environmental costs. Methods for assessing non-market environmental impacts are discussed in Section 4.6.1.2.

Atkins (2018) was the most comprehensive study of emergency supply options that was identified. Costs for each emergency supply option were presented as £/megalitre/day in a marginal abatement cost curve as shown in Figure 11. The marginal abatement cost curves format allows for an easy to understand visual representation of options and straightforward integration into water supply planning as the supplier can move up the curve to the daily flow required and quickly estimate the emergency supply cost. However marginal abatement cost curves do not allow uncertainty to be expressed (Sjöstrand, Lindhe, Söderqvist, Dahlqvist, & Rosén, 2019).

The costs of some emergency supply options such as trucking or shipping water can be estimated using market valuation methods. Others, such as the intangible environmental costs of water abstraction beyond environmental limits, need to be estimated using suitable methods discussed in Section 4.6.

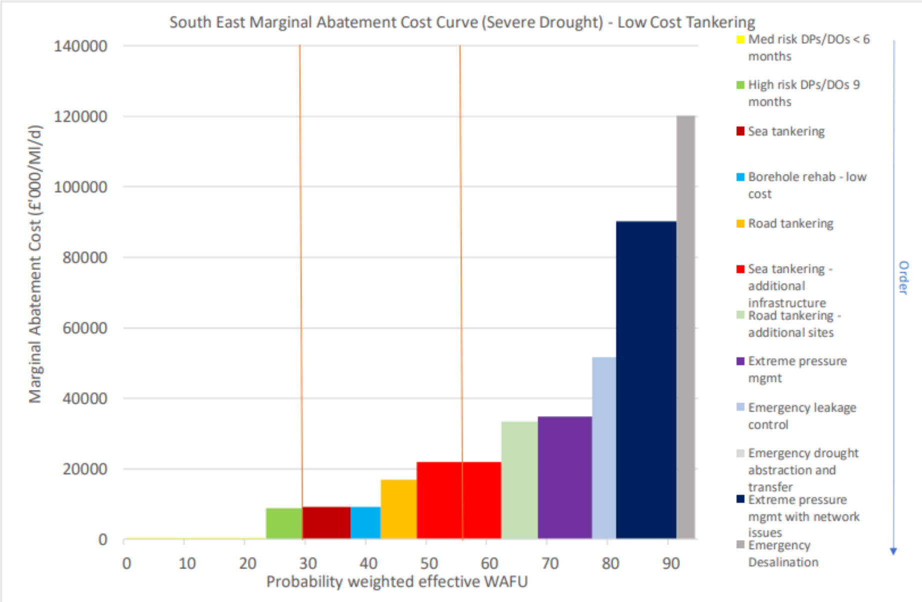


Figure 11. Example of a marginal abatement cost curve for emergency water supply (Atkins, 2018)

Grafton and Ward (2008) applied an avoided cost approach but in a different way, using market data on purchases of supplementary rainwater tanks to estimate the upper bound of how much customers would pay for water.

4.4.3.4 Alternative uses of Water

Surface and groundwater that is taken by an urban water supplier is not available for other uses such as irrigation. The water used or saved by different water supplier polices can valued based on other possible uses for that water that have market prices.

4.4.3.5 Public Health Costs

A review of the public health impacts of drought found limited evidence of the public health impacts of drought in developed countries. The main factors impacts were mental health impacts in rural areas related to loss of livelihood and outbreaks of West Nile Fever (Vos, Dimnik, Hassounah, OConnell, & Landeg, 2021). Both of these factors would not be applicable to many urban areas.

There are several possible public health impacts of drought. Some of these are discussed in DEFRA (2013) and some are based on discussions with water suppliers. No studies were found quantifying these costs.

- Hospitals and other health care centres may not be able to operate due to water disruptions. This would have a very significant health impact. Although it would be expected that hospitals and other healthcare centres would be the last sector to have water shut off by restrictions.

- If water supply was cut off to sections of the network, boil water orders would be issued due to the risk of contamination when pressure is lost. There will be health impacts such as from sickness from those who do not follow this.

There is an opportunity for further study into the public health costs of drought in urban areas as the costs discussed may be significant.

4.4.4 Stated Preference Methods

Stated preference methods use surveys to determine consumers' preferences, such as how much a customer is willing to pay to avoid water restrictions. This section focuses on whether it is appropriate to use stated preference methods to estimate the direct costs to a business or industry from drought restrictions. Literature on stated preference methods focusses only on their use for estimating non-market costs as economists prefer observable market data over surveys (Meyer et al., 2013). No literature was found which discussed whether it was appropriate to estimate direct costs with stated preference methods.

Stated preference methods and the challenges in applying them are discussed in detail in Section 4.1.

Some stated preference studies into households' willingness to pay to avoid water supply restrictions (which are a non-market rather than direct cost) also include a survey of businesses to understand their willingness to pay to avoid water restrictions (Hensher et al., 2006a; Metcalfe & Baker, 2011).

As discussed in Sections 4.4.2 and 4.4.3, it is challenging to use market data to estimate direct drought costs for an urban region. There are a diverse range of industries that could all be affected differently in urban areas and the lack of a direct relationship between water input and production output. AECOM (2016) suggested using stated preference methods to assess direct costs as a check for other methods which was justified due the difficulty of directly linking water scarcity with loss of production for urban businesses compared with agricultural and industrial production.

In conclusion, a representative stated preference study surveying a representative selection of businesses in a region could result in a reasonable estimate of direct costs to businesses. Individual businesses may be better placed to estimate the impact of water disruption than a high level, sector-based impact assumption.

4.5 Methods for Assessing Indirect Costs

4.5.1 Summary and Discussion

4.5.1.1 Types of Methods

The indirect costs of drought represent the complex interactions of a water shortage that ripple through the wider economy.

The following methods for estimating indirect costs were assessed:

- Input-output modelling (I-O)
- Computation general equilibrium modelling (CGE)
- Economic amplification ratio

The methods identified for estimating indirect drought costs mostly require identifying and quantifying direct costs using the methods in Section 4.4. While direct costs are estimated within CGE modelling, the same challenges remain in understanding the proportional impact from partial disruptions that are discussed in Section 4.4.2. Therefore, the robustness of all indirect cost estimation methods relies on the robustness of the underlying assumptions and methodology for assessing direct costs.

I-O and CGE methods have high data, time and expertise requirements. A key component of assessing indirect cost methods was investigating whether applying these methods is worthwhile for an urban water supplier. The reviews of drought cost methods by Logar and van den Bergh (2013) and Meyer et al. (2013) promote these as being the most complete methods for estimating indirect drought costs.

When I-O studies are explored in detail, direct costs are usually estimated using the GDP per sector approach discussed in Section 0. The core assumption behind these direct costs is a resiliency factor for each sector of the economy – the proportional impact the water shortage will have on the GDP of the sector. The basis of these estimated impacts are surveys of local businesses, or professional judgement or developing production functions.

It is questionable whether it is worthwhile for a supplier to spend significant resources on these complex indirect cost methods without improving confidence in the underlying direct cost assumptions. I-O and CGE approaches may be more justifiable in evaluating the costs of previous droughts, where information on actual direct costs is available.

The methods for assessing indirect costs are applicable for all types of indirect costs. With direct costs and non-market costs, different methods may only be appropriate for certain types of cost. As such this section is only split by indirect drought cost estimation method, not by the types of costs.

4.5.1.2 Indirect costs across different industries

A significant finding is that no studies were found estimating the indirect costs of drought in an urban area where office-based knowledge workers make up most of the areas GDP. The closest was a CGE study by Rose and Liao (2005) estimating the impact of water disruption due to earthquakes in Portland, Oregon. The majority of studies that have assessed the indirect costs of droughts focus on the impacts on agriculture, and a small number on urban areas where manufacturing is a major component of local GDP.

The United Kingdom Office for National Statistics (2018) produces input-output analytical tables that include GVA multipliers (Gross Value Added, related to GDP) that provides an approximate upper bound estimate for indirect costs for each sector of the economy. This is discussed further in Section 4.5.

Agricultural and manufacturing related sectors generally have higher GVA multipliers than knowledge industries. For example, the dairy products sector has a multiplier of 3.34 and the petrochemical sector has a multiplier of 2.60. This indicates for every £1 of direct costs, there will be indirect costs of up to £2.34 and £1.60 respectively.

Whereas knowledge-based sectors such as accounting, legal and education services have GVA multipliers of 1.31 or less, indicating indirect costs of £0.31 or less for every £1 of direct costs. This intuitively makes sense that industries that produce physical goods will have greater upstream and downstream impacts that will ripple through the wider economy.

The importance of indirect costs for urban water suppliers will depend on the type of customers. Significant manufacturing or agricultural customers justify investing in a I-O or CGE modelling study. For urban areas where the majority of GDP is from industries where low indirect costs are expected, applying a multiplier to direct costs to estimate total direct and indirect costs may be appropriate. This is defined as the economic amplification ratio (EAR) (K. Jenkins, 2013).

I-O and CGE methods will perform better where there is good information demarcating the local economy into sectors (Logar & van den Bergh, 2013). If this information is not available, a conservative EAR may be appropriate.

4.5.2 Input-output modelling

Input-output (I-O) models takes direct costs that have been previously estimated by sector and estimates the impact on the rest of the economy.

The basis of the methods are I-O tables which are available from government statistics agencies. Each row of an I-O table or matrix represents the monetary output of an industry, and each column represents the industry's inputs. Industry sales are connected to the source of demand such as households, government or exports, expenditure on primary inputs such as wages and consumption of fixed capital (National Institute of Water & Atmospheric Research, 2010).

Availability of existing datasets has a large impact on the resource requirements for these methods due to the cost and complexity of developing a new dataset. For example, Statistics New Zealand (2020) produces national input-output tables that can be adapted into an I-O model. Due to variation in water abundance by location, any model using this information needs to be regionalised. Regionalised I-O tables and a regionalised CGE model are available from private economics consultancies in New Zealand (Insight Economics, 2017; Nixon et al., 2021). However, these models are regionalised based on the local authority boundaries, so may need to be adjusted further to suit the needs of a water supplier.

I-O models have the advantage over the CGE method in that it is easier to apply and have lower data requirements. I-O models also have the flexibility to incorporate direct costs that have been calculated from a variety of methods, whereas the CGE method requires directs costs to be estimated within the model. The drawback of I-O models are the strict substitution assumptions. The recipe of inputs that go into a product is fixed within I-O tables. In reality, firms may be able to substitute some inputs from:

- Other non-drought affected regions or countries,
- Alternative products that are less affected by drought,
- Existing stocks. It may take time for stocks of inputs to be used up and this may be able to be made up later.

As a result of these factors I-O are likely to overestimate indirect costs (Logar & van den Bergh, 2013; Water UK, 2016; Robert A. Young, 2014). The impact of the substitution effect is smaller for smaller events as it will take time for firms to find substitute products. Adaptive regional I-O models address some of the limitations of I-O models (K. Jenkins, 2013).

Green, Viavattene, and Thompson (2011) raise issues with I-O models and CGE models in the context of flood damage assessments. They suggest these methods are more suited to assess the economy-wide impact of an extreme event rather focusing in at a city scale that a utility would be interested in. This may not be as much of an issue for droughts as the focus is on larger drought events - smaller droughts are generally low cost. They also raise issues with the level of skill and experience required to implement these techniques which may limit their usefulness in practice.

A disadvantage of I-O methods compared to most of the other methods assessed in the study is that they do not produce an output in terms of cost or percentage impact that can be directly integrated into water supply modelling. The I-O model itself will need to be integrated into the water supply modelling process and an I-O model run will need to be applied for each scenario being tested. Direct costs need to be estimated first for each policy option being investigated, and then the I-O model applied to estimate indirect costs. This is a significant restriction and adds additional complexity to applying the method in urban areas.

Table 7 shows a selection of I-O studies from literature that were reviewed to assess the methods suitability for assessing costs in urban areas. The economic amplification ratio (total direct and indirect costs divided by direct costs) was also reported to give an indication of the range of possible values from 1.23 to 2.

I-O modelling is commonly applied to estimating indirect drought in agricultural areas. The only study identified that included non-drought costs was Martin-Ortega et al. (2012) which still had 59% agricultural direct costs.

Table 7. Selection of I-O modelling studies

Study	**Focus**	**Comment**	**Economic amplification ratio (EAR)**
Martin-Ortega et al. (2012)	Comprehensive study of urban area and (including indirect costs)	59% of direct costs are related to agricultural losses or flower growing.	1.77
K. Jenkins (2013)	Indirect costs under climate change in Spain. Focus on agriculture.	Indirect losses were forecast to increase over time in higher carbon emission scenarios. Higher indirect losses were forecast for longer droughts than for shorter droughts. Adaptive regional I-O model.	1.23 for a historical drought 1.32 for short term droughts, 1.57 for longer term droughts
Pérez and Barreiro-Hurlé (2009)	Drought in Ebro Basin, Spain. Focus on agriculture and hydropower	Focus on agriculture and hydropower.	1.99

Crawford-Brown et al. (2013)	Impact of climate change on London's economy	Not specifically focused on drought. General study into impacts of various climate change impacts. Adaptive regional I-O model.	Between 1.3 and 2

4.5.3 Computational general equilibrium modelling

CGE models are more sophisticated models that also make use of input-output tables. They allow for more flexibility than I-O models as they allow dynamic substitution of inputs. Whereas I-O models are restricted by the assumption there is no substitution between inputs, which may result in costs being overestimated.

The CGE method still has limitations in that it assumes optimal behaviour of consumers and producers and it has significantly higher data requirements than I-O modelling (Logar & van den Bergh, 2013). CGE models can estimate direct and indirect costs. While direct costs are estimated within CGE modelling, the same challenges remain in understanding the proportional impact from partial disruptions that are discussed in Section 4.4.2. Therefore, the robustness still relise on the robustness of the underlying assumptions and methodology for assessing direct costs.

The method has been located within the indirect costs section as given the significant resource requirements, it is only likely to applied if the supplier is interested in indirect costs.

As with I-O modelling, CGE modelling will needs to be integrated into the water supply modelling process. This is a significant restriction and adds additional complexity to applying the method in urban areas.

Table 8 shows a selection of CGE studies from literature that reviewed to assess the methods suitability for assessing costs in urban areas. The economic amplification ratio (total direct and indirect costs divided by direct costs) was also reported to give an indication of the range of possible values.

As with I-O modelling, CGE modelling does not produce an output that can be directly integrated into water supply modelling. Rose and Liao (2005) proposes a method for separating direct and indirect costs and identifying the EAR. CGE modelling, by default does not separate direct and indirect costs, making it difficult to compare CGE results with other methods.

No CGE studies were found assessing drought costs in urban areas. Rose and Liao (2005) assessed the impacts of a water shortage caused by an earthquake in Portland, USA. An approximately 50% reduction in water supply was assumed along with assumptions surrounding the resilience of sectors to water shortages.

One other relevant CGE study by Carrera, Standardi, Bosello, and Mysiak (2015) assessed the impacts of floods events on both rural and urban areas in northern Italy. Both of these studies produced similar economic amplification ratios of 1.19-1.22.

Several CGE studies assessing agricultural drought costs were reviewed however these did not present results separated by direct and indirect cost so the economic amplification ratio could not be estimated (Berrittella, Hoekstra, Rehdanz, Roson, & Tol, 2007; Nixon et al., 2021; Pauw et al., 2011; Wittwer, 2015; Wittwer & Griffith, 2010).

Table 8. Selection of CGE modelling studies

Study	Focus	Comment	Economic amplification ratio (EAR)
Rose and Liao (2005)	Urban suppler, significant manufacturing component of GDP	Focus on significant disruption caused by an earthquake. Universal 50% reduction in water supply is different from the more targeted cuts for drought water restrictions.	1.22
Carrera et al. (2015)	Economic impact of flood events in Italy. All sectors of the economy.	Flooding impacts rather than drought.	1.19-1.22

4.5.4 Economic Amplification Ratio

The economic amplification ratio (EAR) is the ratio of total direct and indirect costs to the direct costs from a disaster (K. Jenkins, 2013). The advantage of this method is that it is simple to apply and has very low data requirements. Water industry studies that have applied this method include Water UK (2016) and AECOM (2016).

To apply this method, subtract one from the EAR and multiply it by the estimate of direct costs. A single overall EAR ratio can be applied, or an EAR per sector. The method is simple to integrate into water supply planning all as all that is required is a single multiplier.

EAR values from literature from I-O modelling are shown in Table 7 and give range from 1.23-2.0. Values from CGE are shown in Table 8 and range from 1.19-1.23.

As discussed in Section 4.5.2, I-O modelling has a limitation of not accounting for substitution effects so can tend to overestimate indirect costs and therefore EAR. The EAR results from CGE are likely to be more accurate.

The K. Jenkins (2013) I-O study found that more severe and longer duration droughts had a higher EAR. The Rose and Liao (2005) CGE study assumed an approximately 50% reduction in water supply which is higher than restrictions applied in many drought events. indicates the EAR could be lower than 1.22 in a less severe drought.

A portion of the costs in the two CGE studies is related to manufacturing and agricultural losses. As discussed in Section 4.5.1.2, the review of GVA multipliers indicated urban areas where knowledge-based service sectors make up a large portion of regional GPD may have lower indirect costs than sectors that produce physical goods.

GVA multiplier values share similar limitations to the I-O method in that substitution effects are not accounted for. GVA multiplier values have a further restriction in that they assume only one sector at a time is affected which does not reflect the interconnected nature of drought impacts and may lead to double counting (United Kingdom Office for National Statistics, 2018). For example, the agriculture GVA multiplier considers the downstream impacts less food production will have on the food processing sector. However drought impacts on the food processing sector may mean it would have had its output reduced anyway. (Water UK, 2016) Both of these limitations serve to increase the indirect cost estimate. So GVA multiplier values should be seen as an upper bound estimate.

The approximately 1.2 EAR suggested by the CGE studies appears a reasonable value based on the information that was reviewed. A conservative, lower value may be appropriate in urban areas where knowledge-based service sectors dominate.

4.5.5 Indirect Costs of Increased Fire Risk

An indirect impact of waters supply disruption during a drought is preventing water from being available for firefighting, increasing the risk of fire related damages.

There are studies that discuss the link between drought and the cost forest fires such as Littell, Peterson, Riley, Liu, and Luce (2016) and Lynch (2004).

Other studies identify the increased fire risk caused water supply disruption in an earthquake to be one of the largest components of the total economic cost of earthquake (J. Daniell, Khazai, Wenzel, & Vervaeck, 2012; J. E. Daniell, Schaefer, & Wenzel, 2017; King et al., 1997)

The indirect cost of increased fire risk was not considered within this study but is worthy of further investigation.

4.6 Methods for Assessing Non-market Costs

4.6.1 Introduction

Non-market valuation is a well-established field that is regularly used in decision-making to quantify the preferences of the community. As the name suggests, non-market goods are not traded in a market so do not have an observable market price (Robert A. Young, 2014). These costs can be challenging to place a monetary value on. The gradual onset of droughts compared to other natural disasters can make them particularly difficult to estimate (Markantonis et al., 2011). The two most significant non-market costs for urban droughts are:

- The value of avoiding household restrictions. This cost involves assessment of the welfare impact from water restrictions on households and how much households would be willing to pay to avoid such restrictions.

- The environmental impacts of water abstraction beyond minimum environmental flows, including on ecological, recreational, spiritual and cultural values.

The non-market costs associated with cultural values and political or reputational impacts are discussed at the end of this section. It is not proposed to quantify these in the present study.

Methods for valuing non-market costs 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

4.6.1.1 Impact of restrictions on households

Households would clearly prefer not to endure water restrictions such as on watering their gardens or having their water cut off entirely. Stated preference methods can estimate households' willingness to pay (WTP) to avoid water supply restrictions, discussed in Section 4.6.2. There are also approaches that estimate these costs using market valuation methods which are discussed in Section 4.6.5.

4.6.1.2 Environmental Impacts of Abstraction

There is less research on how human activities exacerbate the impacts of drought on the environment than on how drought impacts human social and economic activities (Lake, 2011). Quantifying the environmental impacts of water abstraction is particularly challenging as there are two layers of uncertainty:

1. First, the environmental impacts of taking water beyond minimum environmental flows (from either surface or groundwater) need to be estimated. For example, a decrease in ecological indicators or suitability of a waterway for recreational use.

2. Then, the costs of the environmental impact need to be quantified. For example, estimating the dollar value of the decrease in ecological indicators or recreational usage.

These two factors cannot be evaluated independently and are likely to require separate studies. Estimating environmental impacts is a complex field that is not the focus of this research and could be the focus of a separate targeted study given its complexity. This research includes some limited discussion of non-market costs but such discussion is not intended to be comprehensive.

The options for quantifying the costs of the environmental impacts are to conduct an original stated preference study (Section 4.6.2), revealed preference study (Section 4.6.3) or to transfer the results from a previous primary study (Section 4.6.4).

The environmental impacts of drought in urban areas are linked with water abstraction from groundwater and surface water. This is especially relevant for emergency abstraction beyond environmental limits.

For the purposes of this study, environmental impacts are defined broadly as all use and non-use values that could be influenced by water supplier policy decisions. These include ecology, carbon sequestration, recreation, food gathering and cultural impacts.

Non-market valuation of environmental values is a well-established field with orders of magnitude more studies than the number of studies into the value households place on avoiding water supply restrictions. For example, Marsh and Mkwara (2013) identified 13 studies for non-market valuation (both stated preference revealed preference studies) associated with freshwater just for the Waikato River in New Zealand. This review compared 80 non-market valuation studies from 16 countries and concluded that due to large variation in values, results were site-specific and not applicable elsewhere. There is more likely to be more variation in the value placed on waterways is more local and personal than the value people place on not having to endure water restrictions.

Due to the large volume of literature, and the location-specific nature of environmental values, methods are discussed in more general terms for environmental costs than for household WTP to avoid restrictions.

4.6.1.3 Changes in non-market preferences over time

Values and preferences of a community change over time and would be expected to be different at the end of a 20-50 year planning period than at the start.

There has been an estimated 38-fold increase in laws to protect the environment between 1972 and 2019 (Kumar, Ugirashebuja, Carnwath, Tamminen, & Boyd, 2019). This would suggest that people’s willingness to pay to protect or improve environmental outcomes would also be increasing. However no strong evidence was found to support this. In the absence of this evidence, the default assumption should be that non-market valuation preferences stay consistent over the planning period.

Surprising little research was found into the stability of non-market valuation survey results over long time periods. Results have generally been found them to be relatively consistent over short periods up to 5 years. For longer periods of 20 years preferences were not as stable (Skourtos, Kontogianni, & Harrison, 2009). The vast majority of studies only investigated changes in the short term of less than 5 years. A study investigating changes in the value people placed on recreational value of forests over 20 years found significant changes over time, with the value placed on forests close to urban areas increasing 200% over the period and the value placed on forests further from densely populated areas decreasing by up to 100% (Zandersen, 2005). So it is not entirely clear which direction different values may change over time.

It is clear that cultural attitudes change over time. A study into attitudes (not willingness to pay) showed an increase in belief over a 10-year period that climate change is real and caused by humans. Higher belief was shown by younger generations which would result in the average level increasing over time (Milfont, Zubielevitch, Milojev, & Sibley, 2021).

An example of changing values is from Wellington, New Zealand. It is common knowledge that prior to commissioning of the Moa Point Wastewater treatment plant in 1998, raw wastewater was discharged into the south coast of Wellington. By contrast, in 2021, a pipeline failure resulted in trucks operating 24/7 for five weeks to transport wastewater sludge to a landfill, at a high cost. Discharging wastewater to the sea went from standard practice to unacceptable in 23 years.

Water UK (2016) identifies the trend towards smaller household size affects household willingness to pay. The impact of greater water efficiency is also raised, as this may cause households to value their reduced consumption more highly as they have less flexibility to reduce further.

4.6.2 Stated Preference Methods

Stated preference methods use surveys and statistical methods to infer customers' willingness to pay (WTP) for a non-market good or service. An advantage of stated preference methods is that the surveys can ask about hypothetical future scenarios rather than relying on data from past events. A downside of stated preference methods is that the hypothetical nature of the questions can introduce errors, especially for events that have a low likelihood and high consequence such as severe droughts. Stated preference methods require good survey data and the surveys need to be well designed (Meyer et al., 2013).

An original stated preference method is time and resource-intensive to complete. Stated preference methods are reasonably robust, however it can be difficult to verify the performance of the method as in many cases there are no alternative methods (Logar & van den Bergh, 2013).

There are two main types of stated preference methods, contingent valuation (CV) and choice experiments. Contingent valuation (CV) involves surveying willingness to pay to avoid a change in a specific environmental good or service or their willingness to accept its deterioration for various levels of compensation. Studies that have compared CV with other economic valuation methods have found CV studies slightly overstate the actual value (Logar & van den Bergh, 2013; Meyer et al., 2013).

Choice experiments (CE) are a similar method to CV that asks people to choose between different bundles of goods or services of which price is just one factor. They generally avoid the biases associated with CV methods however are more difficult to implement (Robert A. Young, 2014). An example CE survey is shown in Figure 12 which shows how CE asks respondents to trade-off between options, rather than being asked willingness to pay more directly as in CV surveys. Also attached to the survey would be an explanation of what each level of restriction represents (McNair & Ward, 2012).

Figure 12. Example choice experiment survey from McNair and Ward (2012)

		CURRENT PACKAGE	PACKAGE A	PACKAGE B
RESTRICTIONS ON HOUSEHOLD WATER USE				
Expected number of years spent in each level of restrictions over the next 20 years:	No restrictions	0	0	3
	Water conservation measures	9	8	9
	Stage 1	4	4	4
	Stage 2	4	4	4
	Stage 3	2	2	0
	Stage 4	1	2	0
	State of Emergency	0	0	0
THE COST TO YOUR HOUSEHOLD				
Your ongoing annual water and sewerage bill		$0 more than your current bill	$100 less than your current bill	$350 more than your current bill
If these were the only three options available to you, which option would you choose?		☐	☐	☐
If Package A and Package B were the only two options available to you, which option would you choose?			☐	☐

An ideal primary study would also ask for demographic information from each respondent such as age, education, household income or people per household. This allows results to be expressed as a parametrised function of the site characteristics. This function could then be adjusted to the characteristics of the local region of interest.

4.6.2.1 Impact of restrictions on households

Table 9 shows a review of a selection of studies that estimated household WTP to avoid water restrictions. The purpose of this review was to investigate the method robustness by comparing the spread of results and to assess if the format of different studies was suitable for integrating into water supply modelling. The review of studies is also useful for the benefit transfer method discussed in Section 4.6.4. The review is not intended to be comprehensive; it is intended to be illustrative of the types of approaches to the method and to identify challenges.

One existing review of WTP to avoid water restrictions studies was found by Water UK (2016). However, the studies are labelled as “study A, study B” and are not referenced so it is not clear what studies were reviewed.

Where the results are expressed as a function of relevant site characteristics, a selection of these are listed along with the sign of the relationship, + for positive and - for negative. Only parameters that were significant at a 1% level are listed and not all parameters are listed.

Table 9. Selection of stated preference studies - WTP to avoid water restriction studies

Study	Type of study	WTP to Avoid Water Restrictions (NZD, 2021)[1]	Comments
(Metcalfe & Baker, 2011)	Choice experiment study, London, United Kingdom 2006	\$5 for households and \$117 for businesses to avoid one day of L3 restrictions (outdoor watering ban) \$129 for households and \$2057 for businesses to avoid one day of L4 restrictions (rotating water cuts)	Result format of \$/household/day/water restriction fits easily into water supply modelling. Results are not expressed as a parametrised function of the site characteristics
(Hensher, Shore, & Train, 2006b)	Choice experiment study, Canberra, Australia 2003	\$353 for households \$353 for businesses to avoid consistent L3 restrictions over a year (outdoor watering ban) \$1 for households and \$1 for businesses to avoid one day of L3 restrictions	Result format of \$/household/year /water restriction fits easily into water supply modelling where multiyear restrictions are common. Values are in terms of WTP to avoid restrictions every day for a year, so result divided by 365 to estimate per day value. Results are not expressed as a parametrised function of the site characteristics

[1] All values are expressed in 2021 New Zealand Dollars. Values are inflated to 2021 values based on information from the relevant central bank, and then converted to New Zealand dollars.

Study	Type of study	WTP to Avoid Water Restrictions (NZD, 2021)[1]	Comments
(McNair & Ward, 2012)	Choice experiment study, Canberra, Australia 2012	\$256 per household for 5% reduction in likelihood of L3 water restrictions. (outdoor watering ban) \$14 for households to avoid one day of L3 restrictions	Results are expressed in terms of WTP to for 5% reduction in likelihood of a full year long restriction. Multiplied by 20 to estimate WTP to avoid a certain full year restriction. Results are not expressed as a parametrised function of the site characteristics
(Wilson et al., 2021)	2010 Brisbane survey Willingness to pay to ensure continuous supply.	\$1.07 m^3 plus \$44/quarter fixed charge per household to ensure continuous water supply with minimum restrictions.	The definition of "minimum restrictions" is not clear. This would make it difficult to integrate into water supply planning. Results are expressed as a parametrised function of site characteristics including: Age (-), education (+), has pet (-), number of people in household. Income was not significant.
(Cooper, Burton, & Crase, 2011a; Cooper et al., 2019)	Comparison of two CV studies in 2008 and 2012. Urban and rural cities and towns in Victoria and New South Wales, Australia.	\$7-\$150 per year to avoid all restriction for all respondents to the study. \$191-\$333 if protest responses who state they will not even pay \$0 to avoid restrictions are excluded. \$249 for New South Wales, based on this study (NSW Department of Industry, 2018)	Respondents are simply asked to indicate their WTP to avoid water restrictions – there is no description of the water restrictions represent. Some respondents may have been envisioning having water cut off entirely or minor restrictions such as alternative days of garden watering. The five point scale used (definitely no, no, unsure, yes, definitely yes) meant that the impact of an "unsure" was uncertain. This results in the range of possible WTP values. Parameters include: Income (+), education (+), has lawn (+).

Study	Type of study	WTP to Avoid Water Restrictions (NZD, 2021)[1]	Comments
Water UK (2016)	Review of studies	**Households:** $0.5 (low), $2.2 (central), $5.4 (high) to avoid one day of L3 restrictions. (outdoor watering ban) $87 (low), $173 (central), $346 (high) to avoid one day of L4 restrictions (rotating water cuts) **Businesses:** $468 (low), $974 (central), $1666 (high) to avoid one day of L4 restrictions (rotating water cuts)	Review of 16 studies into WTP to avoid water supply restrictions. It is not clear which studies were reviewed as it is not referenced. Therefore no information on where and when the studies were completed. Some studies are labelled as CV and CE methods.
(Griffin & Mjelde, 2000)	Northern Colorado, USA Contingent valuation	WTP = $40 + $0.46 x (% water shortage) + $0.75 x (days of shortage)	For 10% to 30% water shortfalls. Results are expressed as a parametrised function of site characteristics

Comparison of Results of WTP to Avoid Water Restrictions - Robustness

It is difficult to compare results between the different studies due to differences in preferences between locations and difference in formats of results. The Metcalfe and Baker (2011) and Water UK (2016) studies in the UK estimated similar WTP for both households and businesses. This may be expected as Water UK (2016) likely used Metcalfe and Baker (2011) as one of the studies it reviewed.

A key finding is that households have a low WTP to avoid less severe restrictions such as outdoor watering bans. Households have a much higher WTP to avoid more severe restrictions where water will be cut off to customers.

This aligns with studies into the price elasticity of demand of water supply. Demand for water for watering gardens is much more elastic than water for more essential uses such as sanitation and cooking (Zhongming, Linong, Xiaona, Wangqiang, & Wei, 2021).

Retesting a method using a separate sample from the same population provides an indication of the robustness of the method. Hensher et al. (2006a) and McNair and Ward (2012) are both CE studies with broadly similar survey designs in Canberra Australia. The results were very different, with WTP figures of $1 and $14 respectively to avoid one full day of water supply restrictions. McNair and Ward (2012) attributes the difference to the population’s preference to the exposure to a significant drought in the intervening years.

Exposure to drought may be a contributing factor to higher WTP. Cooper et al. (2019) found that willingness to pay to avoid water restrictions had some variation when surveys were conducted in times of relative water shortage. However an order of magnitude difference in results raises questions about the robustness of the methodology. As a non-expert practitioner in the field of non-market valuation, it is difficult to explain why this difference is so large. It raises the question about other similar studies and whether they would these also produce such varied results if reproduced again.

Format of Results – ease of integration into water supply modelling

There was a wide variety in how willingness to pay to avoid water restrictions were expressed which makes it difficult to compare the consistency of results. Results need to expressed in a format that allows integration into water supply planning. Metcalfe and Baker (2011) study in London expressed costs in terms of WTP to avoid one day restriction per restriction level. Linking results to water supplier restriction levels allows results to easily be integrated into water supply modelling as discussed in the drought cost framework in Chapter 5. A period of days as a time period is appropriate in this example as drought periods are expected to be in the order of 90 days.

Hensher et al. (2006a) and McNair and Ward (2012) studies in Canberra, Australia use the format of WTP to reduce the likelihood of a full year of restrictions. This is appropriate given the long multiyear dry spells that can occur in Australia.

Other studies express results in a format that would be difficult to integrate into water supply modelling. Wilson et al. (2021) expresses WTP in terms of a cost per m^3 plus a fixed cost for continuous water supply with minimum restrictions. The challenge with this approach is that continuous water supply with minimum restrictions is not clearly defined and is not linked to a specific likelihood of drought or restrictions. Customers cannot be expected to estimate their WTP to avoid restrictions unless the nature of the restrictions and how often they might occur is clearly expressed.

Griffin and Mjelde (2000) found a WTP to avoid water restrictions of any duration and then a linear relationship between WTP and % water shortage, albeit only up to a 30% shortage. An issue with assessing WTP to avoid a percentage reduction in water use is that it does not realistically represent how suppliers will reduce water demand. Suppliers cannot flick a switch to reduce customer demand, they must apply restrictions. Asking a customer their WTP to avoid a ban on outdoor watering is more tangible and may get more realistic responses.

Non-linear relationship between drought duration and WTP – ease of integration into water supply modelling

Willingness to pay values for avoiding one day of drought costs does not consider the possibly non-linear impact of prolonged restrictions on willingness to pay (Hall et al., 2020).

It is possible that households do not mind shorter duration restrictions, and WTP increases as restrictions are longer. Such a relationship was suggested for businesses and industry by Chang et al. (2002).

Alternatively, Griffin and Mjelde (2000) suggests there is a lump sum value placed on avoiding severe restrictions of any duration, then a value per day following this. The lump sum value reflects the shock households may face of having their water cut off when it may have never occurred before in their lifetime. It is not clear which is the most appropriate between drought duration and WTP. This area is worthy of further study.

CV or CE studies for Household WTP to avoid Restrictions – Robustness

The CV studies by Griffin and Mjelde (2000) and Cooper et al. (2011a) noted a significant portion of respondents as protest votes where people state they are not willing to pay anything to reduce the likelihood of restrictions, or give nonsensical answers. The authors suggest that many see water as a public good that people have an inalienable right to access, and that people may view water bills as a tax rather than paying for a service.

Protest votes were not mentioned in the CE studies where customers are not directly asked how much they are willing to pay for a change in restriction likelihood. This suggests that CE studies are more appropriate than CV for getting an accurate indication of household WTP to avoid restrictions. CE surveys such as the example in Figure 12 force the respondent to confront the reality that water supply level of service is a trade-off between cost and the risk of shortages.

Conclusion – stated preference methods for household restrictions

The ideal stated preference study for household WTP to avoid restrictions would:

- Express results in terms of WTP per household to avoid one day of a specific level of water restriction. Or per one month or one year if that is more suitable to the typical drought lengths.

- Express results as a function of the demographic information from the site, to allow transfer to other locations

- It is not clear what the most appropriate format is for WTP in terms of duration. There may be a lump sum WTP to avoid restrictions of any duration.

4.6.2.2 Environmental Cost of Abstraction

Stated preference studies to estimate environmental costs is a well-established field. The effort and resources to complete an original stated preference study are high and robustness would be expected to be reasonable to good (Logar & van den Bergh, 2013; Robert A. Young, 2014). There are orders of magnitude more existing stated preference studies estimating environmental costs than studies estimating WTP to avoid water restrictions.

For these reasons, this section focuses primarily on the challenge of linking environmental costs to water supply policy. No previous studies were found that provided practical guidance on how a supplier would estimate environmental costs of drought and integrate into its decision making.

Estimating the environmental costs of water abstraction requires multiple steps. A supplier makes a policy decision (abstraction of a certain amount, for a certain duration) which will cause environmental impacts (negative impacts on ecology, recreation etc.) and then finally the associated environmental cost of the impacts can be estimated.

Stated preference methods can be used for the final step of estimating environmental costs. However, the whole process needs to be understood in order to integrate the environmental costs into water supply planning.

Format for Expressing Environmental Impacts

Environmental impacts are used to inform environmental costs. As such, studies into both impacts and costs are required. The environmental impacts of water abstraction need to be in a format that corresponds to the method used to estimate the environmental costs.

Water UK (2016) proposed a range of indicators of environmental impacts that could practicably be linked to supplier policy decisions:

- Area of water bodies affected by restrictions multiplied by drought duration;
- Number of days environmental minimum flows are breached; or
- Number of days emergency supply permits are applied that allow abstraction beyond minimum environmental flows.

It is possible that there are existing relevant studies for the location of interest in either environmental impacts or the environmental costs. To save resources and time, it may be prudent for a supplier to make use of these existing studies (Benefit transfer – Section 4.6.4) and formulate any new studies to match the same results format as the existing studies.

For example, the United Kingdom Environment Agency (2013a) provides estimates in monetary terms for the benefits of increasing the ecological status of surface waterways along a scale of levels, such as from poor to moderate, and moderate to good. The cost of a change in level is then quantified in terms of £/km of river/year. To make use of this study into environmental costs, any assessment of environmental impacts would need to use the same scale – poor to moderate, and moderate to good etc.

Alternatively, in New Zealand there are standard values listed by the New Zealand Treasury (2021) for cost benefit analysis that were developed from stated preference studies (Resource Economics Ltd, 2020). Results are expressed in terms of $/adult/year for a 1% increase in water quality outcome for water clarity, human health risk (swimability) and ecological quality. To use this study into environmental costs, environmental impacts would need to be assessed in terms of percentage change in water quality outcomes.

Applying national-level studies such as the UK and New Zealand examples has the advantage of being able to apply acceptable existing values from original stated preference studies. However, care must be taken in ensuring the original studies are fit for purpose. Both of the examples focus on long term changes in environmental impacts, whereas the environmental impacts from abstraction will be of a shorter duration, taking some time to recover after a drought event to pre-drought status. Recovery of ecosystems from the low flows of drought is not a very well researched area (DEFRA, 2013).

Assessing the Impact of Surface Water Abstraction

The impact of taking surface flows beyond environmental limits is dependent on the volume that is taken and the duration (Beca, 2008). The volume taken may be linked to environmental limits or minimum residual flows in the waterway.

The duration of drought, and therefore the duration of emergency water takes, varies by location. For example, in Australia droughts can last for multiple years, whereas in the United Kingdom a dry period of 8-18 months would be expected to cause severe drought conditions (Water UK, 2016). In the case study in Chapter 6 in Wellington, New Zealand, severe droughts are only likely to last a few weeks due to frequent rainfall.

The highest environmental impacts are likely to be associated with the most significant takes when a drought is at its most severe (DEFRA, 2013). The focus when assessing the impact of surface abstraction during a drought should therefore be on the likely impacts of short-term emergency abstraction to avoid the worst impacts at the height of a drought.

A water supplier may have limits or consent conditions on the amount of water it can take from a particular waterway. In this situation it may be possible to simplify the assessment of the environmental impacts of abstraction because the level of abstraction (and therefore the impacts) are consistent in all policy scenarios being assessed. The amount of water a supplier will consistently take in all scenarios may be linked to the environmental flows, the specific flow to sustain the habitats and ecosystems of a river or stream (Zhongming et al., 2021). If all policy scenarios assume that the maximum permitted flow will be taken during a drought event then any base level environmental degradation and subsequent costs can be assumed to be identical.

Even at the minimum environmental flow, there may be a base level of degradation in a waterway. The focus of assessing the impacts of surface abstraction should therefore be on the specific *additional* impact of emergency water takes beyond environmental flows during a drought.

Abstraction from waterways can have a range of impacts on the ecology of a waterway such as on invertebrates, plants, fish or algae. The long term ecological impact of a short term reduction in flows may be relatively small. Dewson, James, and Death (2007) tested a month long 89-98% reduction in flow at several small streams in New Zealand. They found minimal impact on the number and diversity of invertebrates in the streams. The density of invertebrates increased as they accumulated in the areas of the stream where flow remained, then quickly returned to its pre-reduction levels once flow returned.

Other studies also found a level of increased stress to invertebrate communities during significant low flows but recovered rapidly once flow returned, provided some flow remained (DEFRA, 2013; Ledger & Hildrew, 2001; Wright, Clarke, Gunn, Kneebone, & Davy-Bowker, 2004).

Environmental impacts will vary by location and by the level and duration of abstraction. A site-specific assessment on ecological impact would be required to accurately estimate the impact of a given level of abstraction on environmental outcomes.

Assessing Impact of Groundwater Abstraction

There is less understanding of the impact of drought on groundwater than surface water (Lake, 2011). A key feature of groundwater and droughts is that there is a lag between drought onset and groundwater levels. For example, in the Murray-Darling Basin, Australia, the Millennium drought in the early 2000s, the peak impact on groundwater water was recorded over a year after the greatest impact on surface water had passed (Tweed, Leblanc, & Cartwright, 2009).

This lag can avoid part of the challenge with surface water abstraction during a drought in that peak demand on the surface source is when it is at its lowest level.

As with surface water, the impacts of groundwater abstraction will vary greatly from site to site. Possible impacts include depleting the groundwater reserves that could be used for other purposes such as agriculture, downstream flow impact on groundwater fed sources, and preventing saltwater intrusion. It is likely to be more difficult to estimate the environmental impacts from groundwater abstraction than for surface water (DEFRA, 2013).

4.6.3 Revealed Preference Methods

4.6.3.1 Overview

Revealed preference methods use surveys and statistical methods to infer customers' willingness to pay (WTP) for a non-market good or service. For example, the recreational values of a river can be inferred by studying people's travel duration and cost to get there. Data and resource requirements are moderate to high and comparable to an original stated preference study (Robert A. Young, 2014).

A revealed preference method would generally be considered more robust than stated preference methods as the values are estimated based on real, observable behaviour, rather than a survey. However, the types of drought costs that can be estimated using revealed preference methods are much more limited than those that can be estimated by stated preference methods (Meyer et al., 2013).

4.6.3.2 Impact of restrictions on households

Hedonic price modelling is a revealed preference method often used in environmental economics to link land prices with the service it provides. It has been applied to estimate drought costs in the agricultural sector however is not appropriate for urban water suppliers (Logar & van den Bergh, 2013).

4.6.3.3 Environmental or Recreational Values

There are limited applications for revealed preference values in an urban drought context. The main application that was identified was to assess the impact on recreational values from abstraction, such as people not being able to swim or kayak in their local river because of the additional abstraction for water supply during a drought. Travel cost and time can be used to infer the minimum value of a recreational journey (Robert A Young & Loomis, 2014).

As with all environmental values, it is important to separate out the impact from abstraction from the recreational impacts on natural low flows during a dry period.

4.6.4 Benefit Transfer

Benefit transfer uses results from existing primary studies to estimate non-market costs or benefits based for the target policy site. The method is especially useful where no original studies are available, and resources or time are limited.

The literature on benefit transfer is well established. There are key criteria that are required to ensure reasonably accurate benefit transfer. These include having high quality primary studies with a sufficiently large number of respondents, sound methodology and an accurate empirical approach (Johnston et al., 2015). Benefit transfer has moderate resource and data requirements and needs to be performed by expert practitioners. The literature is clear on the risks of poorly performed benefit transfers, where inappropriate original studies are transferred or insufficient adjustments are made to account for differences between the original study site and the site of interest (Logar & van den Bergh, 2013).

The ability of benefit transfer to fit within water supply planning is dependent on the format of results of previous studies. Some studies may not be usable due to the format of their results. Whereas the results of an original stated or revealed preference study can be tailored to ensure they can easily fit within a water supplier's planning process.

Errors and Approaches to Benefit Transfer

Errors in benefit transfer can be characterised as errors in the original study (measurement errors), and errors during the transfer of values (generalisation errors).

There are multiple approaches to benefit transfer that could be applied to assess willingness to pay to avoid water restrictions, starting with those that require the least time and resources (Champ, 2003; Johnston et al., 2015; Sharp & Kerr, 2005)

Direct transfer takes the values estimated at a study site, or the average of multiple study sites, and transfers them directly to the site of interest without any adjustments to account for the differences between sites. Some limited or ad hoc adjustments may be made. The accuracy of the transfer is only as good as the accuracy of the original study, and the similarity between the source and target sites.

There is a higher risk of both measurement and generalisation errors in direct transfer. There is a risk that the original study is not appropriate

Benefit transfer function– assumes that the willingness to pay estimate of an original study is a function of the characteristics of the site. For example, WTP to avoid restrictions from an original study may be a function of income, age, education or whether the individual has a pool or a garden. The WTP to avoid restrictions could then be transferred by plugging in the values specific to the site of interest into the function from the original study. This approach allows the requirement of close similarity between sites to be relaxed slightly. Although closer sites will still be more accurate. The benefit function is generally applied on the study side. Benefit transfer function transfers generally outperform direct transfers as differences between sites increase.

Meta-analysis – similar to benefit function transfer but has the benefit of being applied to the results of multiple studies. This can allow for differences in approaches and possible biases among studies to be statistically controlled for.

4.6.5 Market valuation of Loss of Consumer Welfare

Market valuation techniques have been used to assess the consumer welfare losses from water restrictions by using the market price of water. There are challenges in applying this method as water is not a typical market good.

Water suppliers generally charge a flat volumetric rate for water, or apply progressive tiered pricing, where an initial volume is charged at a lower rate than higher volumes.

Other suppliers do not charge by water volume at all. This makes it difficult to estimate a demand curve for water. Customers cannot choose to pay more or less for a different level of service, or switch provider (Robert A. Young, 2014).

Grafton and Ward (2008) estimated a demand curve for water in Sydney, Australia using demand and supplier price data and data on purchases of rainwater tanks. It was assumed that rainwater tanks had been purchased to offset the impact of water restrictions so the price per m^3 of water supplied by tanks and the number of tanks sold could be considered a substitute for water supplied by local authorities and used to estimate another data point in the demand curve. This is an innovative approach that was not found in any other studies.

Garcia-Valiñas (2006) applied a similar approach in Seville, Spain based on quarterly water bill data and other economic information.

The basis of these studies in estimating welfare losses from aggregate water demand and prices is questionable due to the nature of water supply demand. A portion of water use for essential use such as sanitation and cooking where the demand is inelastic and insensitive to price. Water demand for outdoor use is much more elastic (Zhongming et al., 2021). It is not clear how responsive customers really were to price when water price is low. Griffin and Mjelde (2000) found that most customers are not conscious of their water use and water bill where it makes up a small share of household budgets. Brozović et al. (2007) did not believe there was sufficient empirical data to estimate household demand during a water shortage.

Despite these limitations, Logar and van den Bergh (2013) consider the precision of market valuation studies for assessing household welfare losses to generally good.

4.6.6 Other Non-market Values

4.6.6.1 Cultural Values

In identifying all drought costs it would be remiss not to mention cultural costs. The quantification of such costs in water supply is an important issue as indicated by its attention by the *United Nations World Water Development Report 2021: Valuing Water* (UNESCO, 2021 #31). The attempts to quantify cultural values such as the value of water to indigenous groups is complex and contested and is a discrete field of study in its own right. The assessment of such costs accordingly falls outside the scope of the present research. Nonetheless, the valuation of non-market costs is mentioned in relation to the Wellington Water case study in Chapter 6 to provide context into the difficulty of assessing such costs.

4.6.7 Political or Reputational Costs

The Australian water resource planning guidelines WSAA (2008) theorised that the "political" cost of water restrictions could be higher than the "private" willingness to pay to avoid restrictions. For this reason, utilities may be pushed towards encouraging conservation rather than enforcing restrictions even if non-market valuation techniques may indicate they are appropriate.

The political fallout from a drought have the potential to be significant but have not been assessed in this research. The political costs of drought warrant study in their own right. Costs could include the supplier being reformed or fast-tracking capital projects that would not have been done otherwise.

CHAPTER 5 FRAMEWORK FOR INTEGRATING THE COST OF DROUGHT IN WATER SUPPLY PLANNING

5.1 Objectives of the Framework

The purpose of assessing the cost of drought is to inform the optimal level of water supply investment. There are different types of drought costs. To accurately estimate the cost of drought the assessment must be comprehensive so as to not over or underestimate the total cost. An over or underestimation may have significant implications for planning decisions.

It is important that methods of assessing drought costs are compared within an appropriate framework. This study develops a drought cost framework with an aim to:

- provide a practical approach for a water supplier to integrate the cost of drought into its water supply planning;
- facilitate the application of different cost-estimation methods (assessed in Chapter 4); and
- consider the unique features of droughts in urban areas and how these influence water suppliers' decisions.

Within the framework a drought is defined as an event where a water supplier applies water restrictions. An implication is that the same rainfall conditions could affect suppliers very differently. A supplier with minimal water reserves could experience frequent drought while a supplier with very large reserves could theoretically never expect drought. The reasons for linking drought to a water suppliers' restrictions is discussed later in this section.

This framework is built on a conceptual framework proposed by Freire-González et al. (2017b) which defines the unique features of urban drought that need to be considered when assessing drought costs, specifically the division between short term and long term decision making for a water supplier. This core concepts of this framework were adapted and expanded with the aim of creating a practical methodology for suppliers to apply.

The framework in this study is also informed by a range of studies into the cost of drought in water supply planning including those from literature (Martin-Ortega et al., 2012), water industry standards (WSAA, 2005) and water industry studies (AECOM, 2016; Marsden Jacob Associates, 2022; Water UK, 2016).

5.2 Overview of Proposed Framework

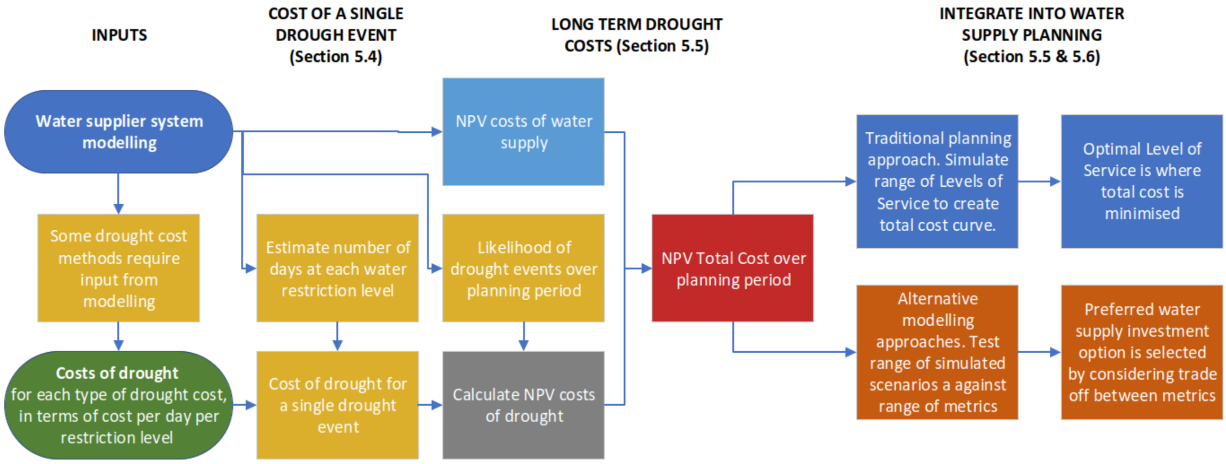


Figure 13. Proposed framework for integrating the cost of drought into water supply planning investment decisions

Figure 11 gives an overview of the framework, starting with the key inputs of water supply modelling data and estimates of the costs of drought, estimated using the methods discussed in Chapter 4.

Section 5.4 is the core of framework, discussing a simplified approach to estimating drought costs in the short run for a single drought event.

Section 5.5 discusses how net present value (NPV) of drought costs and water supply costs are estimated in the long run over the water supplier's planning period, typically 30 years.

Section 5.5 also discusses a conventional approach to water supply planning with the aim of minimising total costs under one set of planning assumptions.

Section 5.6 discusses how the framework could fit within alternative water supply planning approaches.

5.3 Why comprehensive assessment is needed

An assessment of drought costs will only be useful to suppliers if it is accurate. As such, to best inform network planning decisions, it is fundamental that an assessment of drought costs is comprehensive. That is, an assessment must include the full range of potential costs. As discussed in Chapter 4, costs fall into different categories, including direct, indirect and non-market. If some types of costs are overlooked, the total drought cost will likely be underestimated. An under or over-estimation of drought costs could have significant ramifications for network planning decisions. For example, as discussed later in this chapter, if NPV drought costs are overestimated, the framework will recommend an improved level of service target resulting in overinvestment in water supply.

Table 10 summarises a selection of studies into the cost of drought, split by category of drought cost. As outlined in the table, surprisingly few studies were comprehensive in considering all types of drought cost.

In some circumstances it may be appropriate for a supplier not to estimate certain types of drought cost, for example if such costs were negligible. However, it is critical that such an exclusion be a conscious one. A supplier should nonetheless consider each type of drought cost and outline its reasons for excluding certain costs from its assessment.

Table 10. Types of drought costs in selected of drought cost studies

Study	Direct	Indirect	Non-market
Martin-Ortega et al. (2012) Assessment of total cost of 2007/2008 Barcelona Drought	25% (€404M) Direct costs to wider economy 5% (€85M) Water supplier costs	24%, (€378M) Indirect costs to wider economy	43% (€691M) Non-market welfare loss from household restrictions 3% (€51M) Environmental impacts
Katie Jenkins, Dobson, Decker, and Hall (2021) Estimate of annual economic impact of drought in England and Wales	59.4% (£3.90M)	40.6% (£2.67M)	Not assessed
AECOM (2016) Estimate of drought cost in England for a worst case “Extreme” three-year drought in 2050	55% (£43,488M)	Discussed but not assessed	45% (£35,958M) Non-market from household restrictions 0.2% (£35,958M) Non-market environmental cost
Rose and Liao (2005) Estimate of impact of water shortages from an earthquake in Portland	82% ($24,3990M)	17.8% ($5,197M)	Not assessed

5.4 Cost of Drought in the Short Run During a Single Drought Event

5.4.1 Overview

Figure 14 illustrates the cost of drought in the short run during a single drought event. Hydraulic capital, the infrastructure involved in the production, storage, and transport of water such as dams, treatment plants, desalination plants, are fixed in the short run (Freire-González et al., 2017a). A supplier has key decisions during a drought event: when to implement each successive level of water supply restriction, or whether to implement emergency water supply options.

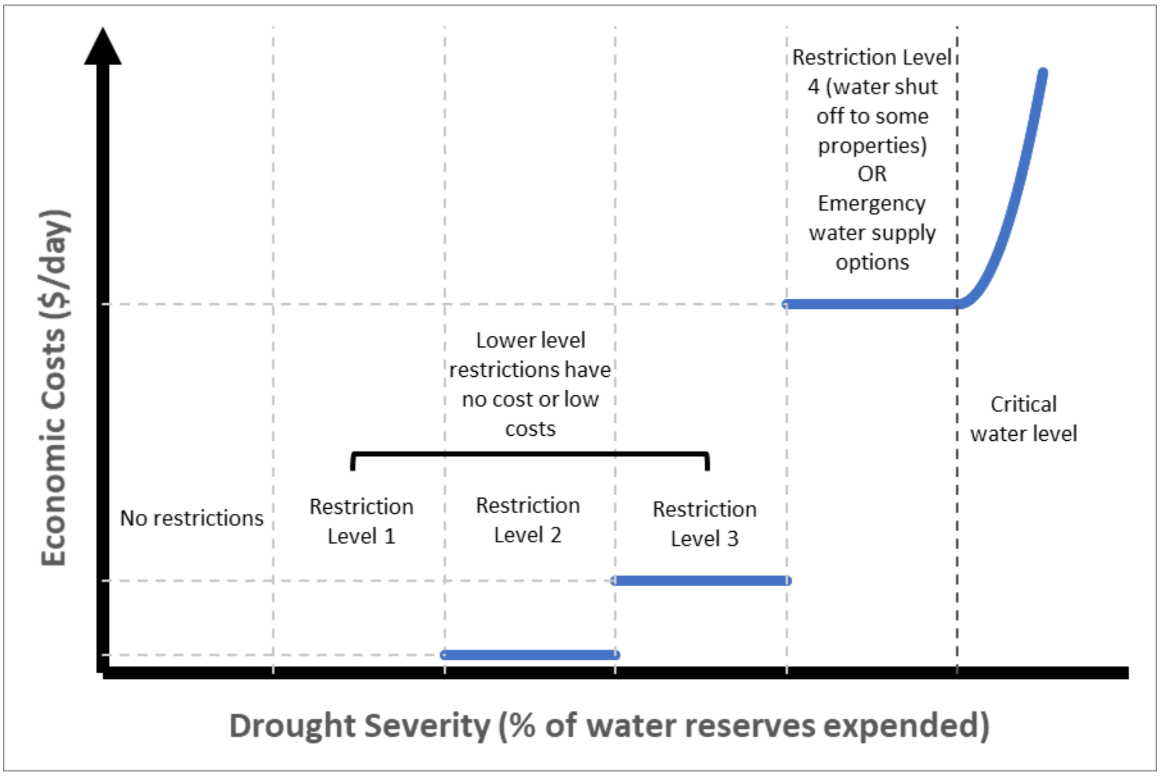


Figure 14. Drought cost curve in the short term. Adapted from Figure 4, Freire-González et al. (2017a).

5.4.2 Cost of Restrictions

Drought costs are linked to the supplier's restriction levels and increase as a discrete step-change curve (Freire-González et al., 2017a). The literature review of water supply planning showed suppliers in the United Kingdom, Australia and New Zealand follow a similar structure of applying restrictions of increasing severity, and that the majority of drought costs in urban areas can be linked to restriction level (Erlanger & Neal, 2005; UKWIR, 2002a; Wellington Water, 2022c). This allows the existing drought management plans for suppliers to be integrated into the drought cost framework as suppliers should already be able to estimate the frequency they expect to impose drought restrictions.

Lower level restrictions, such as limiting watering of gardens, have a relatively low cost and can be insignificant compared to total drought cost as shown in Figure 14. Much more significant costs are associated with more severe restrictions that cut off supply to customers. Households are willing to pay significant amounts to avoid such restrictions and the impacts on non-household users can be large. Section 4.6.2.1 provides a range of example studies showing the relatively low costs of low-level restrictions compared to more severe restrictions.

Figure 14 illustrates how in urban environments the cost of drought will only be felt once the policy decision to implement water restrictions is imposed. Dry periods that do result in water reserves decreasing below the Level 2 restriction threshold will effectively have no cost. The implication is that a supplier could theoretically build enough resilience in their water supply system such that restrictions are never implemented and there are effectively no droughts.

The cost of urban drought is not directly linked to rainfall in the way agricultural drought costs can be. Instead, the cost of urban drought is a function of rainfall, suppliers' short-term decisions on when to implement restrictions, and suppliers' long-term decisions on the level water supply investment.

Drought cost is expressed in days at each restriction level. Days was selected as the most appropriate unit of time based on studies in the United Kingdom where drought durations are in the same magnitude as for the New Zealand case study in the next chapter. In areas where droughts events and subsequent restrictions can be over multiple years a longer unit of time than days would be appropriate. Appropriate units for drought duration and alternative assumptions to a linear relationship between costs and example studies are discussed in Section 4.6.2.1 for household impacts, 4.4.2.3 for costs to businesses and Section 4.6.2 for environmental costs.

Linking drought costs to days of restriction assumes that drought costs scale linearly with number of days of restriction. Alternative assumptions may be appropriate to correspond with input studies. For example, some studies into drought costs to businesses discussed in Section 4.4.2.3 suggest drought costs per day increase as a drought progresses. Other studies into the impacts on droughts on households discussed in Section 4.6.2.1 suggest a lump sum to represent households aversion to a drought of any duration, plus a daily drought cost.

5.4.3 Cost of Emergency Water Supply

A supplier may in some circumstances not have a real decision between restrictions or emergency supply. An alternative assumption proposed by the UK National Infrastructure Commission (2018) is that shutting off water to a city would be seen as politically unthinkable. Instead, suppliers and governments would commit all available resources to source emergency water supply, even at very high financial and environmental costs. Sources could include trucking or shipping water, or abstraction from surface or groundwater beyond environmental limits.

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.

5.4.4 Critical Water Level

There is a critical water level in which a supplier's reserves are depleted and drought costs increase beyond planned restriction levels. The cost of drought past this critical water level is not explored in detail within this framework. It was assumed that for the majority of suppliers, a combination reliable base sources, such as from groundwater or a large river, that in combination with severe restrictions could prevent the critical level being reached.

The costs of a drought beyond the critical water level could still be estimated using the methods discussed in Chapter 4, however the costs would be more difficult to estimate as they would not be tied to clearly defined supplier restriction levels.

5.5 Integrating Drought Cost into Water Supply Planning – conventional approach

The cost of drought needs to be integrated within long-term water supply planning to have an influence on water supply decision-making. This section focuses on a simplified approach where the aim is to minimise total cost under a single set of supply and demand assumptions. All costs are net present value (NPV) costs over the water supplier's planning period, typically of 30 years.

Figure 15Figure 15 shows the key trade-off for suppliers in network planning and investment decisions in the long run: weighing up the relative costs of drought with the costs of enhancing water supply that might go unused. The optimal level of service is where the total cost of water supply plus drought costs is at a minimum. Note that a shift to the left indicates an improvement in level of service as this lowers the annual likelihood of water restrictions.

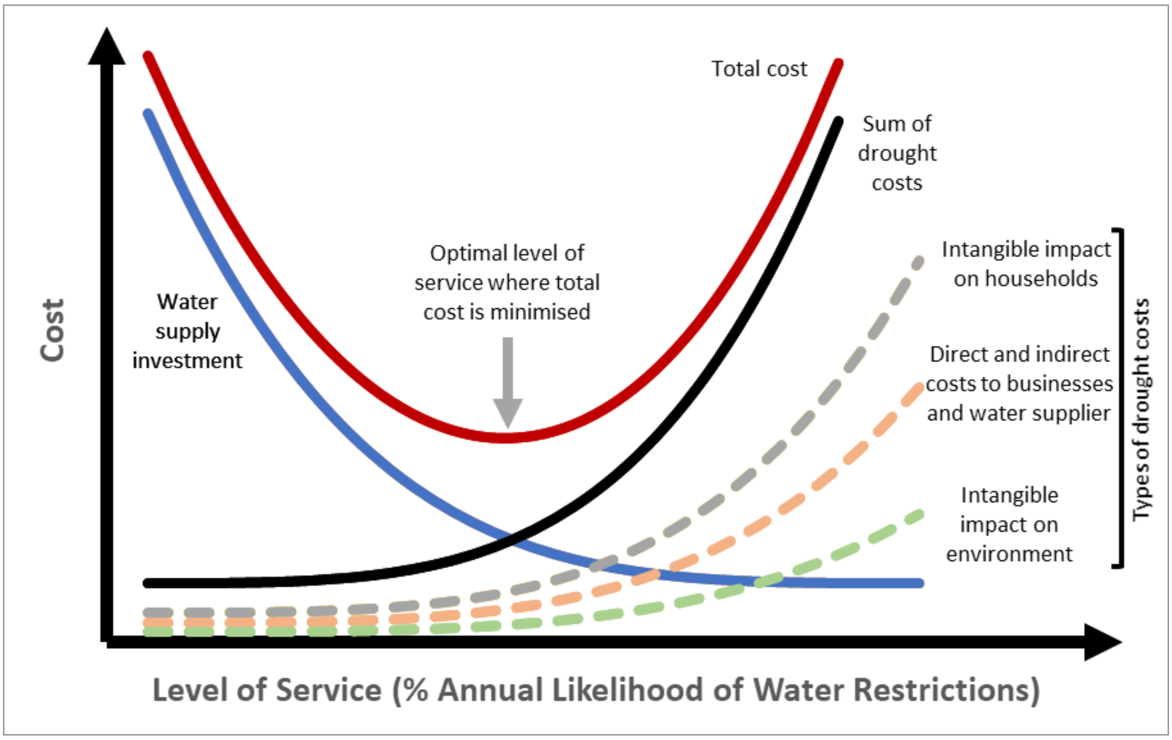


Figure 15. Trade-offs when selecting the optimal level of water supply investment. Adapted from WSAA (2005).

Figure 15 also shows that if all types of drought cost are not considered, for example, only intangible household costs, the optimal level of service would shift to the right and the optimal level of water supply investment would be lower.

The purpose of assessing the cost of drought is to inform the optimal level of water supply investment. To select an optimal level of investment a drought cost curve needs to be developed which requires estimating drought costs at a range of levels of service. The cost of water supply investment also needs to be estimated at a range of levels of service. Estimating drought cost for one event, such as for an historical event, is not sufficient to inform investment decisions on its own.

Due to the long timeframes involved in planning, designing and constructing a new water supply source, suppliers must plan for future sources many years in advance. For the purposes of this framework, water supply sources can mean a source to provide additional supply, or options that reduce demand such as installing water meters or fixing leaks. These essentially perform the same role because they reduce the likelihood of drought. Both types of options have associated Capex and Opex costs.

New water sources need to be built to maintain a given level of service (assuming demand increases over time due to population growth).

Meeting different levels of service may involve investing in the same water sources, however the timing may be brought forward or pushed back. This is illustrated in the example in Figure 16 where the same two water sources are built for all three level of service targets, but at different points in time. New water sources can be identified by the points of sharp improvement in level of service.

It is standard practice when assessing costs and benefits to discount future costs and benefits by a discount rate to estimate the net present value (NPV). At a higher level of service target (i.e. lower likelihood of restrictions), water sources will need to be built earlier so there will have a higher NPV water supply cost over a given period. Assessing the total water supply NPV (Capex and Opex) for a series of different level of service targets can be used to develop the water supply investment curve in Figure 15.

Figure 16. Example performance curves of time for various level of service targets

5.6 Integrating drought costs into a range of water supply modelling approaches

The framework shown in Figure 15 takes a conventional approach to water supply planning, considering minimising economic cost as the only metric for selecting the optimal level of water supply investment. It is also based on a single set of supply and demand assumptions.

There are many uncertainties in long-term water supply planning, specifically the influence of climate change and forecasting future demand. As explored in the literature review in Section 2.4, there are many approaches to dealing with this uncertainty in water supply modelling. A simple approach is to apply a headroom buffer to demand. More complex approaches include testing water supply investment options against a wide range of plausible future scenarios which can help with understanding future climate and demand uncertainty. The performance of a water supply system can be judged by several metrics other than economic cost such as flexibility and robustness. These metrics can identify options that perform reasonably well under a wide range of plausible futures, rather than being the performing optimally for a single possible future but poorly in others. These approaches may result in a different mix of supply options being preferred.

Regardless of the water supply planning approach, minimising total economic cost is a key metric that should not be ignored in any water supply modelling approach.

Despite these developments in water supply planning approaches, a target Level of Service approach is still popular (Hall, Borgomeo, Bruce, Di Mauro, & Mortazavi-Naeini, 2019). A LoS approach has advantages, including that it is straight forward for water suppliers to implement (because they can use their existing planning and modelling approach) and LoS is a concept that is simple to communicate with public.

A possible next step in advancing the framework proposed in this chapter is to consider a third variable such as robustness to minimise for as well as drought costs and water supply costs. Figure 6 in the literature review illustrates how this approach might work.

5.7 Conclusion

This chapter presents a practical framework for a water supplier to integrate the costs of drought into their long-term water supply investment planning.

The key simplifying assumption of the framework is to link all drought costs to the cost per day at each restriction level. The advantage of this assumption is that thresholds to implement restrictions, how severe restrictions are and who they affect are within the control of the supplier and can be clearly linked within a supplier's existing water supply modelling.

The framework can be used to estimate an optimal level of service for water supply through comparing drought costs with water supply investment costs and minimising total costs. The framework is also flexible enough that it is be possible to integrate within alternative methods of water supply planning where minimising total cost is not the only driver.

The framework presented in the chapter is tested in a case study on the water supply for Wellington, New Zealand in the following Chapter 6.

CHAPTER 6 CASE STUDY OF NEW ZEALAND WATER SUPPLIER

6.1 Introduction/Objectives

This research applies the framework proposed in Chapter 5 and a selection of the methods proposed in Chapter 4 to a case study of Wellington Water, a New Zealand water supplier. The objectives of the case study are twofold: (1) to test different methods to identify their advantages and limitations of the methods, and (2) to provide more detailed recommendations on which methods will be most appropriate for future assessments of urban drought costs. The case study, in applying the methods to industry data, provides insight into practical challenges water suppliers may face when assessing the cost of drought.

Time restrictions and data availability limit the number of methods identified in Chapter 4 that could be tested. In general, methods that require the least time and resources are applied. This generally involves estimating the Wellington values based on relevant primary studies. This would be the likely starting point for a supplier beginning to investigate the cost of drought to indicate the scale of the costs and to help prioritise areas of further research. This case study will help identify challenges and future research opportunities for a supplier taking this approach.

6.1.1 Wellington Water

The case study is based on data from Wellington Water, which manages the water services for over 430,000 people in the cities of Upper Hutt, Lower Hutt, Porirua and Wellington in New Zealand. The Wellington region experiences relatively frequent rainfall throughout the year, even in summer. The water supply system has been developed in recognition of the frequent rainfall with a relatively small amount of network storage. The network is vulnerable in dry periods longer than three months. As a result, emergency water supply options are limited to those that can be implemented in a short timeframe. This also means that restrictions may need to be escalated quickly during a drought period (Wellington Water, 2022b).

This characteristic makes the Wellington region an interesting case study as it is quite different to studies for other water suppliers. For example, and in contrast, some regions in the UK are vulnerable in events lasting from 8-18 months (Water UK, 2016) and some areas in Australia have much larger storage but can face multi-year droughts such as the Millennium drought.

In Wellington, 60-65% of supply is consumed by residential households and the remainder by non-residential customers and to leakage. Water is only supplied to urban areas and there is little agricultural use.

Wellington Water is currently in the process of reviewing its drought management policies. Some information used in this is study are estimates based on professional judgement and discussions with Wellington Water staff and may not necessarily reflect final policy.[2]

Wellington Water's current drought resilience level of service is "Sufficient water is available to meet normal demand except in a drought with a severity of greater than or equal to 1 in 50 years". For the purposes of this study, level of service is expressed as the annual likelihood of water restrictions, making this a 2% annual exceedance probability (AEP) level of service.

6.2 Drought Management Approach

Wellington Water has recently released a drought management plan. The plan is not prescriptive but does outline the likely actions that would be taken during a drought event (Wellington Water, 2022b).

Drought restrictions would be applied progressively as a drought worsened over four levels of increasing severity. Table 11 shows an estimate of supply and demand during

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[2] Notes on file with author

each stage of restriction. Note that due to leakage and commercial demand remaining relatively constant, the vast majority of demand reduction must come from households. Levels of drought restrictions are generally aligned with those in the United Kingdom and levels 1 to 3 generally align with those in Australia (WSAA, 2005).

- Level 1 and Level 2 restrictions are relatively minor such as awareness campaigns and limiting the times of day when residents can water their gardens. The literature review and assessment of methods indicated that customers do not place a strong value in avoiding these types of restrictions and the economic impacts are negligible. Therefore, the cost of these restrictions is not considered.

- Level 3 (L3) restrictions involve a complete ban on outdoor water use such as watering gardens or filling pools. A 20% reduction in total demand is expected compared with a typical peak period (200ML/D reduced to 160ML/D). Communication with Wellington Water suggests that a smaller demand drop demand of 10-15% reduction (200ML/D reduced to 170-180ML/D could be more realistic based on previous experience.

- Level 4 (L4) restrictions include a complete outdoor water use ban and unspecified reductions to indoor water use. A 35% reduction in total demand is expected.

Table 11. Water supply availability and corresponding maximum demand from demand management plan (Wellington Water, 2022b)

	Units	Best Case	Peak Period Typical Case	Later Summer Expected Worse Case	Extreme Case
Expected restriction level	Level	1	1-2	3	4
Total available supply (including network limitations)	ML/d	220	200	160	130
Max commercial demand	ML/d	37	37	39	39
Water loss allowance	ML/d	40	40	45	45
Max residential demand	ML/d	143	123	76	46
	L/person/d	310	265	165	100

The 62% decrease in residential demand and 35% reduction in total demand proposed in the Level 4 restrictions in Table 11 appears unlikely to be feasible through voluntary reductions alone. Two UK studies indicate up to a 10% reduction in demand through voluntary measures and up to a 25% reduction in total demand through severe restrictions where water is cut off for some customers (AECOM, 2016; DEFRA, 2013). When considering the UK figures it is important to note that lower water use in the UK than in Wellington may mean there is less opportunity in Wellington for a reduction in demand. The Wellington Water plan does not explicitly lay out how this significant drop in demand would be achieved. Two plausible approaches that could fit within the drought management are considered and applied within the cost of drought model. Both options are considered substitutes for each other.

1. **Severe Restrictions Approach**. During severe Level 4 restrictions, water would be shut off to sections of the network to reduce demand. Water would be supplied to these households through standpipes for residents to fill containers or bottled water. This corresponds with the Level 4 Emergency Drought Orders in the UK planning framework (Water UK, 2016). This approach introduces health risks as losing pressure would allow the potential for groundwater to contaminate pipes. Boil water notices would need to be issued.

2. **Emergency water supply approach**. An alternative assumption proposed by the UK National Infrastructure Commission (2018) is that shutting off water to a significant urban areas such as Wellington is unthinkable. Instead, local and central government would commit all available resources to source emergency water supply, even at very high financial and environmental costs. L3 restrictions would still be applied. 30-50 ML/D of emergency supply would be required to avoid the severe Level 4 restrictions. The 30 ML/D estimate is from the drought management plan which assumes L3 restrictions will reduce demand by 20%. 50 ML/D is an upper limit that assumes L3 restrictions will

only reduce total demand by 10%, which may be more realistic based on the effectiveness of previous restrictions discussed with Wellington Water staff.[3]

6.3 Wellington Water Supply Network

Wellington Water sources water from three main sites:

- **Te Marua water treatment plant**. It is currently being upgraded to be able to supply 125 ML/D. The model assumes that this upgrade has been completed as this was the system performance data that was available. Water is sourced from the Hutt River through a weir at Kaitoke. Water is stored in the two Macaskill lakes which can store 3350 ML, providing approximately two to three months of storage depending on the availability of other sources. Minimum environmental flows in the Hutt River of 600 L/s (52 ML/D) limits abstraction during dry periods. The 1 in 100 year low flow is 700 L/s (60 ML/D). There is a separate set of back up pumps that can pump up to 84 ML/D from the Hutt River. However, these come under the same consent as the main Kaitoke intake.

- **Waterloo water treatment plant**. Up to 115ML/D is pumped from bores in the Waiwhetū aquifer which is recharged by the Hutt River. The risk of saltwater intrusion in the aquifer limits maximum flow. Modelling of the aquifer indicates a short term sustainable yield of 100 ML/D during stress periods such as those expected during a drought (GWRC, 2014). The aquifer is well understood however there is still a risk that abstraction would need to be limited if saline intrusion was detected through monitoring. Due to the lag between aquifer recharge rate and safe abstraction rate, additional abstraction from the Hutt River would not be expected to affect short term abstraction from the aquifer.

- **Wainuiomata water treatment plant**. Can supply up to 60 ML/D sourced from a the Wainuiomata and Orongorongo rivers and three smaller creeks.

[3] Notes on file with author

Water is drawn directly from the rivers and creeks – there is no storage. The plant can be unusable during even non-drought summers as flows drop below minimum environmental flows. It is therefore unlikely that water would be able to be taken from these rivers during a severe drought while ensuring environmental flows. The minimum flow to operate the plant is 10ML/D.

6.4 Emergency Water Supply Options

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

Options for emergency water supply in Wellington are limited by the short duration of drought events. With only 2-3 months of storage, and L3 restrictions only applying once storage levels are at 40-70% (the threshold varies depending on the time of year), emergency options must be able to be implemented within weeks (Wellington Water, 2022b). Emergency water supply plans from industry in Australia and the UK were reviewed to get an indication of types of emergency options and the timeframes for implementing them (AECOM, 2016; Atkins, 2018; Marsden Jacob Associates, 2022). Several emergency supply options were considered feasible in Wellington based on information provided by Wellington Water.

Options considered feasible:

- Emergency abstraction. Wellington Water has discretion to temporarily reduce environmental flows from 600 L/s to 400L/s, allowing an additional 200 L/s (17.3 ML/D) of abstraction to the Te Marua Treatment Plant.

- Road tankers. Raw water could be transported by road and emptied into the Macaskill storage lakes at Te Marua treatment plant. Some enabling works would be required so tankers could be efficiently filled from water sources and drained into the Macaskill Lakes but these were considered feasible in a short period. 7-10 ML/D is considered feasible from this option.

- Surface abstraction beyond environmental flows. It is possible to abstract all the flow at Kaitoke Weir in the Hutt River, leaving a 600m section of the river dry. This would allow 400 L/s (34.6 ML/D) of additional flow above the drought permit flow. 10 ML/D of abstraction was also considered possible from the two rivers and three streams that feed the Wainuiomata Treatment plant. The environmental impacts of this option are discussed further.

Options not considered feasible:

- Groundwater abstraction beyond environmental limits. Saltwater intrusion into the Waiwhetū aquifer would be catastrophic as the aquifer provides 40% of the Wellington region’s water, and an even greater percentage during summer. It may take a very long time to reverse or be irreversible. Although technically feasible as a short-term option, the cost of this was considered far greater than other emergency options such that it was not considered further.

- Water shipping. This was not considered feasible given the short timeframes and the long distances of travel required for large sea tankers to reach New Zealand (as there are no large sea tankers permanently based in New Zealand). There are also significant enabling works that would be required to connect a sea tanker to the water supply network.

- Emergency desalination plant – enabling works would take too long unless it was completed in advance of a drought. Six months of enabling works are estimated in Atkins (2018).

- Desalination ships. The Royal New Zealand Ship HMNZS Aotearoa has a desalination capacity of 0.1 ML/D which is insignificant. Enabling works would be required to connect a ship to the network.

- Borehole rehabilitation. There are other bores located in the Waiwhetū aquifer. However, the existing pumps to the Waterloo treatment plant already have more capacity than the short-term sustainable yield of the aquifer so no additional flow could be safety abstracted.

Figure 17 shows the marginal cost curve for Wellington Water’s emergency supply options.

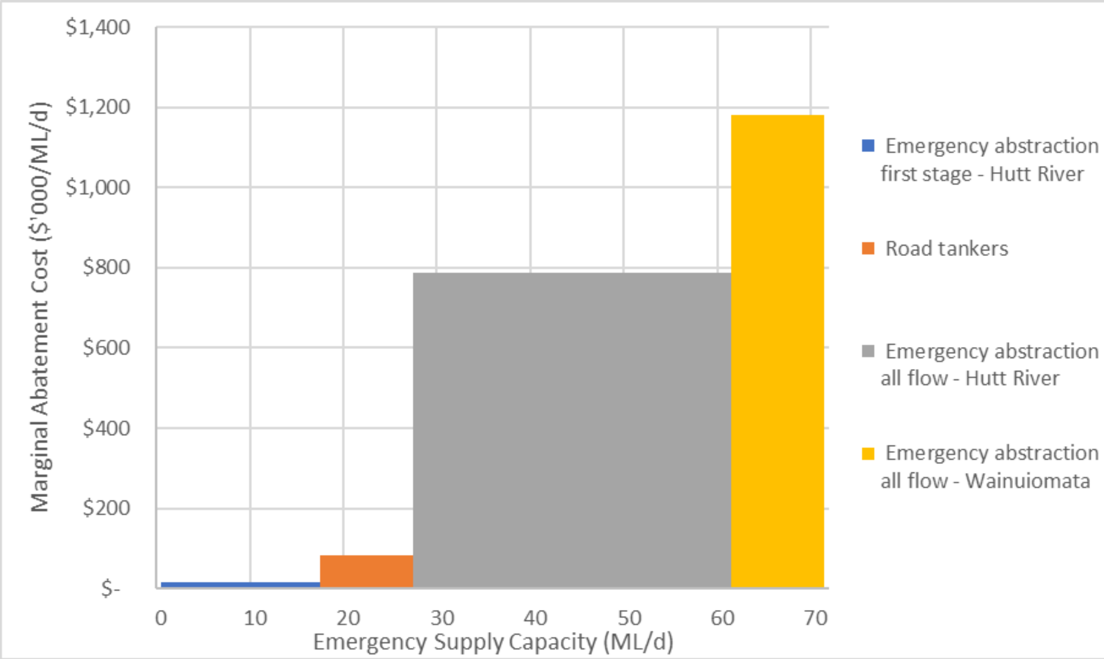


Figure 17. Marginal cost curve for emergency water supply options

6.5 Modelling Approach

6.5.1 Overall Approach

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 available 2020 data. A simplified model of the Wellington Water supply network was developed to demonstrate the proposed cost of drought framework and to test methods for assessing drought costs. Network modelling results are the same as those used in the Wellington Water Economic Case for Providing Residential Water Consumption Information report (Ernst & Young, 2020). The planning period of 2020-2050 was selected as this aligns with the available data from Wellington Water.

Figure 18 summarises the modelling approach, showing how data from Wellington Water and drought costs feeds into the model to estimate a final level of service.

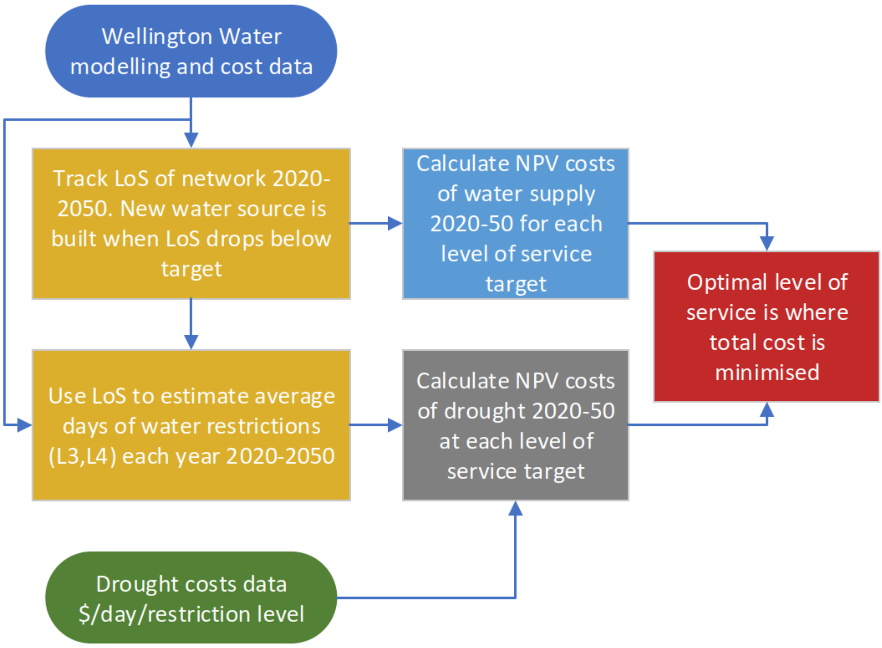


Figure 18. Summary of modelling approach

Wellington Water data includes network modelling results, forecast population increase, and cost estimates for new water sources. Drought cost data is the cost each day of water restriction (L3, L4) for each type of drought cost.

The drought cost model process is repeated for each Level of Service (LoS) target (0.5%, 1%, 2%, 4% AEP). Details of how the model estimates the costs of water supply and the costs of drought are discussed in the following sections.

This model estimates the water supply cost, drought cost and total cost values for each of these LoS scenarios to create cost curves. The lowest total cost and optimum level of service can then be identified.

The drought cost framework from Chapter 5 was applied where the objective is to minimise the total of water supply costs and drought costs over a planning period. The output from the model is an optimal level of service where total cost is at a minimum. This aligns with the conventional planning approach discussed in Chapter 5. The cost of drought was estimated by applying the methods identified in Chapter 4. The cost of water supply was estimated using data received from Wellington Water.

The model is a simplified model which was considered appropriate as the focus of this research is on the cost of drought, not on water supply modelling. In practice, a much wider variety of supply and demand side options would be considered for improving system performance and other criteria than just minimising total cost could also be considered. Nonetheless this model would be a valuable contribution to a wider exercise.

Microsoft Excel and the @RISK add-in was used to create the model and to perform the Monte Carlo simulation.

6.5.2 The Cost of Water Supply

Level of service (LoS) for the Wellington Water supply network is expressed as an annual likelihood of a shortfall in water supply (all water storage is depleted) with normal demand. During a drought event, restrictions would be incrementally imposed to reduce demand below normal levels. For example, Level 4 restrictions may be applied when water storage reaches 30%, meaning Level 4 restrictions will be applied more frequently than the level of service percentage indicates (Wellington Water, 2022b). Therefore, the annual likelihood of each level of water restriction (L3, L4) is not equal to the LoS but can be expressed as a function of the LoS. The current level of service is for a 1 in 50 year/2% annual exceedance probability (AEP) event.

The key simplifying assumption of the model is that the water supply and demand balance is not considered directly. Instead, the model utilises outputs from Wellington Water's supply network modelling, specifically the LoS vs population performance of existing and future water supply options as shown in Figure 19.

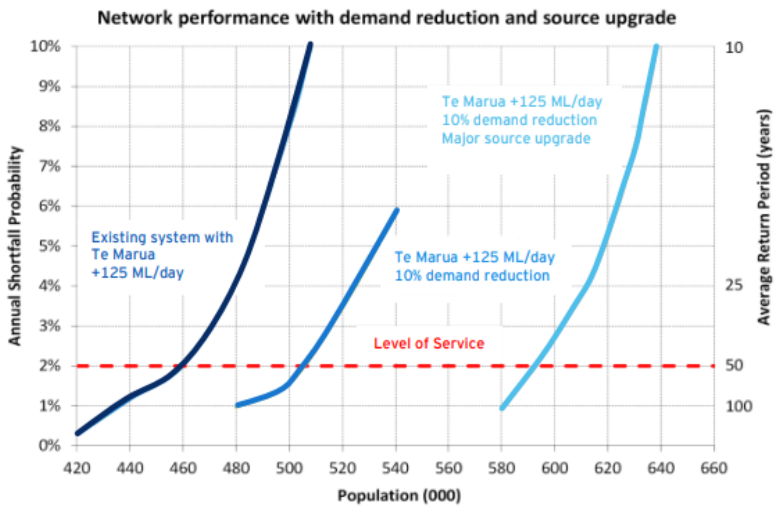


Figure 19. Network level of service at different population levels (Ernst & Young, 2020)

As the projected population increases over time and no new water source is added, the annual likelihood of water restrictions increases. A new water supply source is added once system performance meets the LoS threshold as shown in Figure 20. Sharp improvements in performance indicate installation of a new water source. Exponential functions were fitted performance curves in Figure 19 to estimate down to a 0.2% LoS.

Only two new sources are considered. They are introduced in the following sequence. Each source has upfront capital expenditure (CAPEX) and ongoing operating expenditure (OPEX). Figure 20 shows how the LoS over time for the four scenarios:

- Universal water metering. For the purposes of the model, water metering acts as a new water source by reducing demand by 10% as this decreases the chance of water restrictions. Note that a 10% drop in demand may be conservative. The neighbouring Kapiti Coast District Council installed water meters in 2014 and achieved a 26% decrease in water use (Cole, 2016).

- A new raw water source based on a third storage lake at the Te Marua treatment plant.

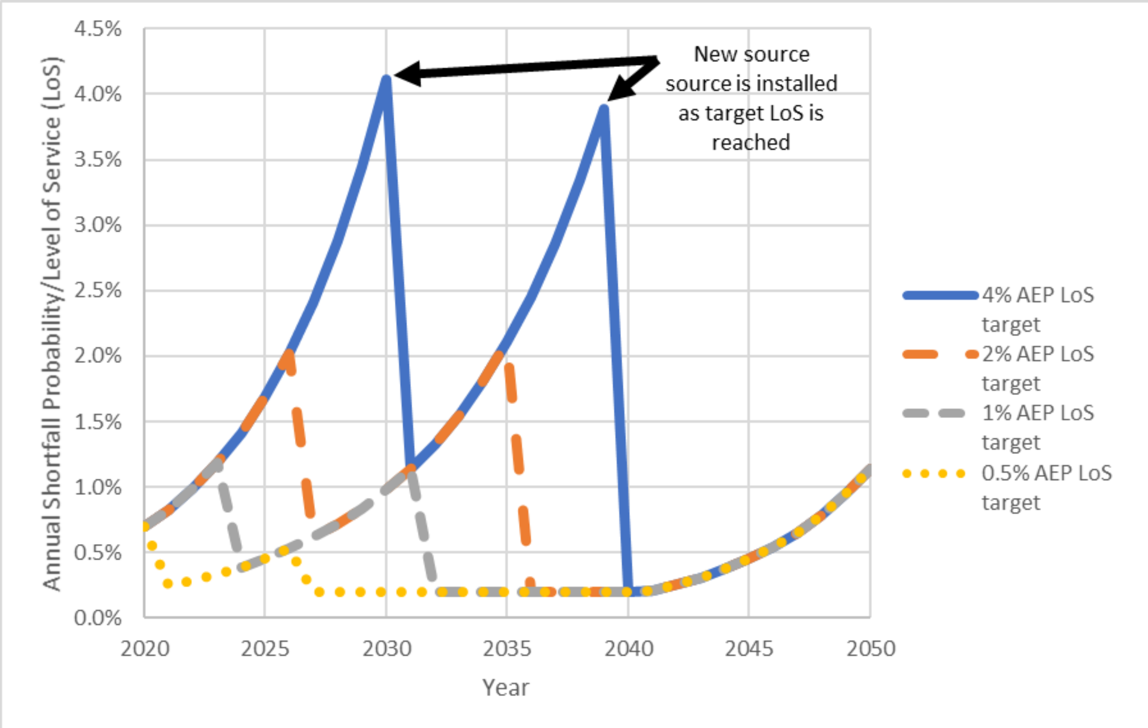


Figure 20. System performance over time under various LoS targets. Sharp improvements in performance indicate installation of a new water source.

Figure 21 shows Wellington Water network modelling results linking each level of service to the annual probability of each level of water restriction (Williams, 2019). Combining the level of service over time shown in Figure 20 with the likelihood of restrictions shown in Figure 21 and assumptions on average drought duration, the number of days of drought year can be estimated.

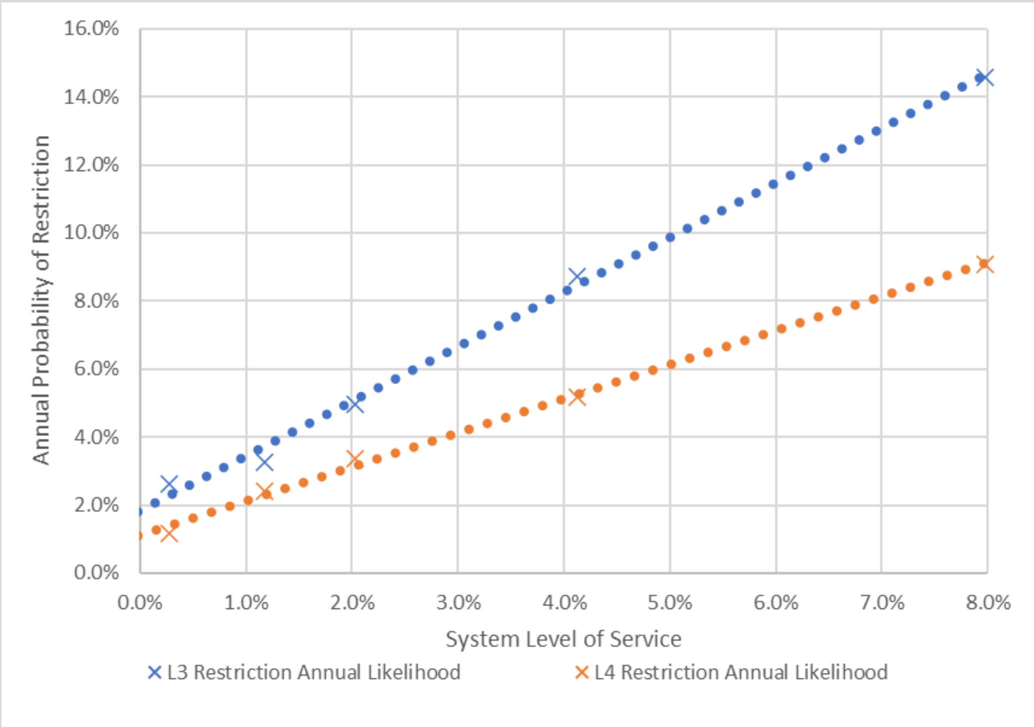


Figure 21. Annual probability of restrictions compared to system level of service. Extrapolated from Williams (2019) and discussion with Wellington Water

The cost of drought is estimated for each year by multiplying the annual restriction likelihood by average drought duration in day and the daily cost of drought. Water supply cost and drought cost are estimated for each year.

6.5.3 The Costs of Drought

The two drought management approaches (severe restriction approach and emergency water supply approach) are integrated into the model in a similar manner. All types of drought cost are estimated in terms of cost per restriction level per day. Details on how each type of drought cost was estimated are described in Section 6.7.

Drought costs are integrated into the model in the following process:

- The cost per day for both Level 3 and Level 4 restriction levels was estimated for each type of drought cost (household cost, environmental costs etc).
- The cost of a single drought event is then estimated by multiplying the per day cost with the average drought duration where Level 3 restrictions are applied and where Level 4 restrictions are applied.

- The cost for each year in the 2020-2050 planning period is then estimated by multiplying the cost per drought by the Level 3 and Level 4 restriction likelihoods. Figure 20 shows the LoS for each year for each LoS target which is then used to determine the Figure 21.

- The NPV cost of drought over the planning period is estimated for each type of drought cost and for total drought.

Total costs for the severe restriction approach, where severe restrictions are applied to households and non-household at the level 4 restriction level, were estimated at:

- $0.7-1.9 million/day of Level 3 restrictions

- $41-95 million/day of Level 4 restrictions

Total drought costs for the emergency supply approach, where emergency water supply replaces Level 4 restrictions, 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

Results are explained more fully in the results section below.

6.6 Approach to uncertainty

There is significant uncertainty in many of the inputs. Some of this is due to lack of data and some of this is due to the inherent uncertainty of the inputs. The approach to uncertainty was to model each input with an appropriate distribution based on available data and appropriate assumptions where data was not available.

Where only a single value was available for an estimate, the general approach was to apply a range of 50% to 200% of the estimated value. Where a range of values was available, a range was selected based on available data. Assumptions linked to the drought cost estimation methods are summarised in Table 12.

Other assumptions linked to the Wellington Water modelling data are summarised in Appendix A.

Monte Carlo simulation analysis was applied with 10,000 iterations to provide a range of possible outcomes. The target output is the optimal level of service, where the sum of water costs and drought costs is at a minimum. Monte Carlo analysis provides a systematic way to assess the sensitivity of the output (LoS %) to each of the input values. This will help direct resources for further research into the inputs that have the greatest impact on which inputs are worth researching further.

The range of optimal LoS is limited to within the range that was tested between 0.5% and a 4% Level of Service. This is because the optimal level of service is fitted as a U-shaped polynomial function. If the optimal LoS is outside the range that is tested, total cost will be either increasing or decreasing over the whole curve so it will not be possible to identify the minimum total cost.

6.7 Methods selected to estimate the cost of drought

Time restrictions and data availability limit the number of methods identified in Chapter 4 that could be tested. In general, methods that require the least time and resources were applied. This limited the available options to mostly finding relevant, similar studies and transferring the costs to Wellington.

The most significant costs identified were:

- The non-market impact on households (severe restriction approach).
- The direct impact on non-household customers (severe restriction approach).
- The non-market impact on the environment (emergency water supply approach).

Table 19 summarises the methods that were applied to each type of cost, the range of estimated costs and the distribution that was applied for the Monte Carlo simulation.

Table 12. Methods applied to estimate types of drought cost

Type of Cost	Method Applied	Unit	Lower estimate	Expected value	Upper Estimate	Distribution
Household impact	Benefit transfer from London study by Metcalfe and Baker (2011)	WTP to avoid one day of L3 restriction	$1	$5	$13	Triangular
		WTP to avoid one day of L4 restriction	$65	$129	$258	Triangular
Direct impact on non-household users	Benefit transfer from London study by Metcalfe and Baker (2011). Also, GDP per sector method.	WTP to avoid one day of L4 restriction	$514	$2,057	$4,114	Triangular
Indirect impact on non-household users	Economic amplification ratio from review of previous studies		1	1.2	2	Pert
Environmental impact	Benefit transfer from Resource Economics Ltd (2020)	Ecological impact - Cost of 1% change in macroinvertebrate community index (MCI)	$3.4	$6.8	$10.2	Triangular
		Swimability impact - Cost of 1% change in human health risk	$2.0	$4.0	$6.0	Triangular

Type of Cost	Method Applied	Unit	Lower estimate	Expected value	Upper Estimate	Distribution
	Own estimate from review of literature	% change in environmental values from L4 emergency abstraction (Ecology and swimability assumed to be 100% correlated)	5%	50%	500%	Pert
Reduction in water per person per day	Market valuation from current Wellington Water volumetric prices.	L3	$0.30	$0.45	$0.61	Triangular
		L4	$0.39	$0.54	$0.70	Triangular
Water supply investment costs	Capex new source 1 (metering)	Capex new source 1 (metering) - Cost	$54,329,500	$108,659,000	$217,318,000	Weibul
	Opex new source 1 (metering)	Opex new source 1 (metering) – Cost per year	$4,155,000	$8,310,000	$16,620,000	Weibul
	Capex new source 2	Capex new source 2 - Cost	$125,000,000	$250,000,000	$500,000,000	Weibul
	Opex new source 2	Opex new source 2 - Cost per year	$1,750,000	$3,500,000	$7,000,000	Weibul

6.7.1 Cost of Household Impact (severe restriction approach)

Choice of Method

Households place a value on avoiding water restrictions. The possible methods for estimating this non-market cost are an original stated preference study, using market data or to transfer the results from a previous stated preference study. Transfer from a previous stated preference study was selected as the preferred option given the time and resource limitations of this study. Using market data was not considered feasible as Wellington Water does not meter customers or charge volumetrically for water.

Selecting a Suitable Study to Transfer Values

A range of studies estimating the non-market impact of water restrictions on households were considered looking for a location with similar characteristics to Wellington with results that fit within the Chapter 5 framework. No local New Zealand studies were found. As discussed in Section 4.6.2.1, the results from some international studies do not fit within the framework.

The key criteria for when looking for suitable studies included locations that had comparable severity of restriction levels in terms of which customers will be affected and how significantly (especially for the most severe Level 4 restrictions which will have the highest cost). Similar household income and similar restriction duration were also considered.

Wellington Water's Level 3 restrictions involve banning all outdoor water usage such as watering gardens which is equivalent to Level 3 restrictions in Australia and in the UK.

Restrictions comparable to Wellington Water's Level 4 restrictions were difficult to determine as the Wellington Water drought management plan and Emergency management plan do not explicitly lay out which customers will be affected. The plans allows significant flexibility in how Wellington Water will react during a Level 4 restriction (Wellington Water, 2022a, 2022c).

As discussed in Section 6.2, it was assumed that during Level 4 restrictions water would be shut off to sections of the network by rotation. This corresponds with the Level 4 Emergency Drought Orders in the UK planning framework. Water would be supplied to these households through standpipes for residents to fill containers or bottled water. Rotating water cuts at Level 4 was considered a reasonable assumption given the significant (67%) reduction in household demand required, and as the groundwater allows a base level of supply so some households will still be able to be supplied.

The Metcalfe and Baker (2011) study in London, UK was considered the most appropriate study to apply to Wellington Water's network. It indicates a WTP of $5 (NZD, 2021) per business per day to avoid Level 3 restrictions and $129 to avoid Level

4 restrictions. As well as having comparable impacts for Level 3 and Level 4 restrictions, London and Wellington have similar yearly income. Household equivalised (per person) disposable income for Wellington in 2019 was $49,000 compared to $59,000 for London (NZD, 2019) with similar average household sizes of 2.6 and 2.7 respectively (Office for National Statistics, 2019; Statistics New Zealand, 2019). No adjustment was made for the approximately 20% higher household income in London compared to Wellington as it was well within the -50% to +100% range of values tested.

The Water UK (2016) study was also considered which compared a range of 16 studies into household WTP to avoid water restrictions and suggested a WTP of $2 (NZD, 2021) per business per day to avoid Level 3 restrictions and $173 to avoid Level 4 restrictions. The 16 studies are not referenced so it not clear what assumptions were made. Nonetheless it is an indication the Metcalfe and Baker (2011) values are of an appropriate magnitude.

The main difference between original study and the Wellington region is the duration of restrictions. Level 4 restrictions are expected to be applied in London for up to three months, whereas in Wellington severe restrictions of three weeks are more likely.

It is not clear what the impact of a shorter restriction duration would have on household WTP to avoid restrictions. 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. Further research in relation to the effect of shorter duration restrictions on WTP would be a valuable contribution to the field.

Range of Values and Distribution

The central value is from Metcalfe and Baker (2011). The range of values for L3 restrictions is from $1 to $13 to reflect the wide range of values in literature, especially in Australian studies (Hensher et al., 2006a; McNair & Ward, 2012).

The range of L4 restriction is from -50% to +100% of the central value based on the range proposed in (Water UK, 2016) from reviewing a range of studies.

The triangular distribution was applied due as a reasonable representation of possible outcomes given the uncertainties in transferring values and lack of available data.

6.7.2 Cost of Non-Household Impact (severe restrictions approach)

Choice of Method

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 25% of each other. Transferring values from an existing stated preference study and the GDP per sector approaches were selected as they both allow high level estimates to be made relatively easily.

Transfer from Stated Preference Method

Results from the Metcalfe and Baker (2011) stated preference study were again applied. It indicates a WTP of a $117 (NZD, 2021) per business 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. The number of businesses in Wellington was based on the number of businesses with at least one employee in the wider Wellington region, scaled based on the number of people that are Wellington Water customers (430,000 out of 547,000) (Infometrics, 2021).

GDP per Sector Approach

An alternative approach was to assess the effect of water shortages on GDP per day for each type of industry in the Wellington Region. Values were again scaled based on the number of Wellington Water customers in the wider Wellington region. Table 13 shows the breakdown of GDP by sector as well as the percentage decrease in GDP per sector, which is the most crucial and most challenging assumption in this method.

The assumed L4 estimates are a high-level estimate based on the UK studies DEFRA (2013) and Water UK (2016). In general, professional office-based sectors were expected to be more resilient to L4 restrictions with GDP reductions of 25% applied.

Sectors such as manufacturing and construction were assumed to be more vulnerable to L4 restrictions so a GDP reduction of 50% was applied.

Rounding to the nearest 25% was considered appropriate given the large uncertainty in both how severe Level 4 restrictions will be and how this will impact GDP.

An average cost per day of Level 4 restrictions was $27.7 million or $1500 per business per day. This is approximately 25% less than transfer method. This is very similar given the significant uncertainties involved and is a positive sign that the results are in the correct order of magnitude.

Table 13. GDP loss estimates by sector in the under Level 4 restrictions. Sector GDP data sourced from Infometrics (2021)

Industry	**Annual GDP regional ($m)**	**Annual GDP adjusted for WWL customers ($m)**	**Share of total**	**Daily GDP ($m)**	**Assumed L4 GDP reduction**	**L4 Losses/day ($m)**
Public Administration and Safety	5,697	4,478	13.1%	12.3	25%	3.1
Professional, Scientific and Technical Services	5,566	4,375	12.8%	12.0	25%	3.0
Financial and Insurance Services	3,625	2,850	8.3%	7.8	25%	2.0
Manufacturing	3,127	2,458	7.2%	6.7	50%	3.4
Health Care and Social Assistance	2,620	2,060	6.0%	5.6	50%	2.8
Information Media and Telecommunications	2,212	1,739	5.1%	4.8	25%	1.2
Rental, Hiring and Real Estate Services	2,156	1,695	4.9%	4.6	25%	1.2
Construction	1,975	1,553	4.5%	4.3	50%	2.1
Retail Trade	1,550	1,218	3.6%	3.3	25%	0.8
Electricity, Gas, Water and Waste Services	1,513	1,189	3.5%	3.3	0%	-
Education and Training	1,436	1,129	3.3%	3.1	25%	0.8
Wholesale Trade	1,270	999	2.9%	2.7	25%	0.7
Transport, Postal and Warehousing	1,242	977	2.8%	2.7	50%	1.3

Industry	Annual GDP regional ($m)	Annual GDP adjusted for WWL customers ($m)	Share of total	Daily GDP ($m)	Assumed L4 GDP reduction	L4 Losses/day ($m)
Other Services	875	688	2.0%	1.9	25%	0.5
Arts and Recreation Services	756	594	1.7%	1.63	25%	0.4
Accommodation and Food Services	696	547	1.6%	1.50	25%	0.4
Administrative and Support Services	672	528	1.5%	1.45	25%	0.4
Agriculture, Forestry and Fishing	317	249	0.7%	0.68	50%	0.3
Mining	35	28	0.1%	0.08	50%	0.0
Owner-Occupied Property Operation	2,997	2,356	6.9%	6.46	25%	1.6
Unallocated	3,285	2,583	7.5%	7.08	25%	1.8
Total	**43,623**	**34,292**	**100%**	**93.95**	**29%**	**27.7**

Impact of Working from Home

Estimates from both methods may be overestimating direct costs on non-household users. A large portion of the Wellington region's GDP is from office-based knowledge industries. As discussed in Section 4.4.2.6, 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.

Range of Values and Distribution

The central value of $2057 per business per day of Level 4 restrictions is from Metcalfe and Baker (2011).

The range of L4 restriction is from -75% to +100% of the central value based on the range proposed in (Water UK, 2016) from reviewing a range of studies.

The triangular distribution was applied due as a reasonable representation of possible outcomes given the uncertainties in transferring values and lack of available data.

6.7.3 Indirect Costs for Non-household Customers (severe restrictions approach)

Choice of Method

An Economic Amplification Factor (EAR) was applied to estimate the indirect costs. This method was selected as it was the most straight forward to apply as discussed in Section 4.5.4. Indirect costs would be expected to make up a relatively low proportion of total drought costs given that office-based knowledge sectors make up a large portion of the Wellington region's economy which have relatively lower indirect costs.

Range of Values and Distribution

The central EAR of 1.2 was applied with a lower limit of 1.0 (zero indirect costs) and an upper limit of 2.0. The central value of 1.2 and the range of values was estimated based on the assessment of discussion of indirect costs in Section 4.5.

The triangular distribution was applied due to a reasonable representation of possible outcomes given the uncertainties in transferring values and lack of available data.

6.7.4 Environmental Impact (Emergency water supply approach)

Choice of Method

The most significant environmental impact in the emergency water supply approach is abstraction from the Hutt River beyond minimum residual flow limits. Approximately 30-50 ML/day is required to avoid the most severe Level 4 restrictions. Section 6.4 discussed the limited options available to meet this supply given the short lead time to droughts in Wellington. Emergency abstraction from the Hutt River was identified as the most feasible option to supply the majority of this flow.

Applying the drought cost framework to Wellington 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 residual flows need to be estimated. Then the value of the impact needs to be estimated.

No primary studies were found assessing household willingness to pay for a change in environmental outcomes in the Hutt River, necessitating transferring values from other studies. New Zealand studies were reviewed with the main criteria being studies that were intended to be general to New Zealand waterways rather than being specific to a single waterway.

The study that was selected as the most suitable was Resource Economics Ltd (2020). The purpose of the study was to quantify the environmental impacts on waterways of a nationwide policy to improve farming practices such as fencing waterways from livestock. The study reviews a range of relevant New Zealand WTP literature. The results in the study have been listed by New Zealand Treasury (2021) as standard values for the improvement of waterway health to use in cost benefit analysis. As such the values were considered the most authoritative and suitable source in the New Zealand literature.

It is not clear that the Resource Economics Ltd (2020) study is entirely fit for purpose as due to its different focus and scale. It estimates WTP to improve waterway health nationwide whereas the Wellington Water case study is focused on WTP to avoid negative impacts in one specific river. WTP to avoid and WTP to improve are subtly different and may result in different WTP from survey respondents. However, the results were considered the best estimate available.

The study presents results in terms of WTP per adult per year for a 1% increase in three separate environmental outcomes in water clarity, human health risk (swimability) and ecological quality in terms of Macroinvertebrate Community Index (MCI).

Recreational impacts were not considered beyond the human health risk factor when swimming. Reduced flows in the Hutt River would limit use for activities such as swimming and kayaking. These impacts were not considered given the short duration of reduction in flow. Recreational impacts are considered indirectly in the human health risk (swimability) value as the river will not be useable for recreation if there are toxic algal blooms in the river.

Abstraction from the Hutt River

The minimum environmental flows at the Hutt River Kaitoke intake is 600 L/s (52 ML/D). In a drought situation, Wellington Water may be able to take an additional 200 L/s (17 ML/D). This additional take was done for three weeks in 2013 when the storage lakes were under maintenance. There were minimal additional long term environmental impact, noting that there is an existing base level of degradation in the river from abstraction. (Clapcott, 2020).

Taking all of the remaining 400 L/s (52 ML/D) would dry the river bed for approximately 600 m before it is joined by tributaries. This occurred multiple times prior to the current consent which started in 2001. No studies were found assessing the impact of taking all the flow from the intake for a short period.

It was assumed that at least 600 L/s (52 ML/D) would be available in the Hutt River, even during a drought event. This was considered a reasonable assumption as the 1 in 100 year low flow rate in the Hutt River is approximately 700 L/s (60.5 ML/D) (Clapcott, 2020).

There is a separate set of back up pumps that can pump up to 84 ML/D from the Hutt River approximately 6km downstream of the main Kaitoke intake. These come under the same consent as the main intake however it may be possible to utilise both the pumps and intake simultaneously to keep at least some flow in the Hutt River.

The current intake weir at Kaitoke acts as a significant obstruction to fish passage further upstream, regardless of flows. Taking additional flow is unlikely to have any further impact on river connectivity. If all of the flow in the river was taken, fish could be relocated downstream from any pools that remained in the river.

Wainuiomata treatment plant

The impact of emergency supply from the Wainuiomata treatment plants was not considered directly as the impact per volume of water taken was considered likely to be greater than from the Hutt River. A high level estimate of 50% higher cost per ML/day was assumed for the marginal cost curve in Figure 17. The plant it regularly unusable during non-drought summers as flows in the streams are below their minimum environmental flows. The minimum flow to operate the plant is 10 ML/d and the five streams and rivers that feed it are relatively small meaning most or all of the flow would likely need to be taken.

Estimating Environmental Impact of Abstraction from the Hutt River

Environmental impacts were assessed in terms of percentage change per year in water clarity, human health risk (swimability) and ecological quality to correspond with the primary study being used. It is important to consider the format of results when transferring values from primary studies as discussed in Section 4.6.1.2. Abstraction beyond environmental limits will have an impact on environmental indicators and the cost of these impacts can then 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. It was assumed that water clarity would not be affected by abstraction.

Ecological Impact Criteria

Taking some flow beyond the minimum residual flow for a short duration is unlikely to have a significant impact on the river ecology (Clapcott, 2020).

Taking more flow, or all the flow at the intake will have a greater impact. No studies were found assessing this impact and it unclear from the literature how significant this will be. Dewson et al. (2007) tested a month-long 89-98% reduction in flow at several small streams in New Zealand and found that macroinvertebrate populations concentrated in the remaining flow and quickly bounced back once flow was restored.

This ecological criterion focuses on macroinvertebrates as an indicator of wider river health so does not directly consider other ecological indicators such as fish abundance. Low flows are unlikely to cause any additional restrictions to fish passage as the Kaitoke weir already prevents fish from migrating upstream.

Human health risk criteria

The main impacts on the human health risk (swimability) criteria are cyanobacteria blooms (commonly referred to as ‘toxic algae’) and faecal contamination from wastewater (not affected by water take so not assessed). Cyanobacteria blooms have killed dogs and pose a risk to humans and have resulted in sections of the Hutt River being closed to swimming in the past.

There is a link between low flows and increased risk of cyanobacteria blooms, as lower flows reduce the ability of the river to dilute nutrients as well as causing higher water temperatures. However, low flows are not necessarily the main cause of the issue. The duration between large rainfall events (> 9x median flow events) that flush the river were identified as the main cause of cyanobacteria blooms, which is not linked to abstraction (Heath, Wood, Brasell, Young, & Ryan, 2015). Notably, there were no significant cyanobacteria issues during 2013 where minimum flows were reduced.

Range of Values and Distribution

The central values of $6.8 and $4.0 were applied for a WTP per adult per year for a 1% change in ecological values and human health risk respectively.

A ±50% range of values with a triangular distribution was applied to reflect that the primary study from which the values were taken had different objectives than the present study so may not be entirely fit for purpose.

A range of 5% minimum, 50% midpoint and 500% maximum range of values with a PERT distribution was applied. The distribution is intended to represent both the large amount of uncertainty and that the indication in the literature that the environmental impact is likely to be on the lower end of the scale. Changes greater than 100% represent the chance that it may take multiple years for the river to recover. The PERT distribution was selected over a triangular distribution due to the very high possible maximum value. A triangular distribution would result in the median value being skewed far higher than the 50% midpoint value.

6.7.5 Cost of Water Tanker (Emergency water supply approach)

The only emergency supply option considered feasible other than increased water takes was transporting water by road tanker. Raw water could be taken from a variety of surface waterways in the region and discharged into the storage lakes at Te Marua at the Hutt River which has good road access.

Road water tankers would be a logistical challenge as:

- almost all of the tankers would need to be brought in from other regions of New Zealand. Only approximately 10 water tankers were registered in the Wellington region and approximately 200 are in the North Island (Taumata Arowai, 2021).

- tankers would need to be filled from multiple sources in the region to limit the impact on any one surface water source.

- some enabling works would be required to efficiently unload the water into the storage lakes.

Trucking up to 10 ML/d of water from various surface sources into the existing storage lakes was considered feasible in an emergency situation (Atkins, 2018). This represents approximately 80 20,000 L trucks doing six round trips each day.

A study into Wellington's water supply planning after an earthquake could be provided by water tankers, milk tankers and even concrete trucks could be utilised at relatively short notice to transport up to 8.7 ML/d of raw water in an emergency. Fonterra (a large milk producer) indicated they had some capacity to assist in an emergency. Fonterra transports up to 80 ML of milk per day by road throughout New Zealand and their peak October/November period does not correspond to the period where drought are most likely in January-March (Hutchison & O'Meara, 2012).

Agreements would need to be reached with neighbouring regions to access water. Wellington Water owns temporary storage tanks that could be set up adjacent to rivers and streams and filled up over time. Tankers could then quickly fill up from these tanks.

An average return trip of 100km was assumed which would give access to surface water sources within the area of the four cities Wellington Water supplies, as well as north in the Wairarapa region.

Table 14 shows a range of sources estimating the cost of bulk road water tankers. A value of $750/ML/km was applied with a ±50% minimum and maximum value and a triangular distribution. The value applied was higher than those in Table 14 to account for the additional set up and logistical costs in setting up a road tanker system.

Table 14. Studies estimating the cost of bulk road water tankers.

Cost	Source	Comment
$222/ML/km (NZD, 2021)[4]	Marsden Jacob Associates (2022)	Estimated based on sum of travel time costs, vehicle operating costs, and externality (pollution) costs built up from information from NSW Government (2020).
$28,500/ML (NZD, 2021)	NSW Department of Industry (2018)	Avoided cost of water carting (distance not provided) from New South Wales cost benefit analysis reference guide.
$380-510/ML/km (NZD, 2021) [5]	Atkins (2018)	£31-40/m3 for a 100 mile round trip (GBP, 2018). Estimated 7 ML/D maximum from one filling site.
$19,000-$32,000 /ML + $420-$700/km (NZD, 2021).	Tankful Ltd (2019)	Commercial water tanker rates in upper North Island, New Zealand.
No costs estimated	Hutchison and O'Meara (2012)	Estimated 8.7ML/D was feasible after an earthquake, utilizing water, milk, roading and concrete trucks to transport non-potable water.

[4] AUD inflated to 2021 prices using Reserve Bank of Australian calculator then converted to NZD at average 2021 rate of 1.0621

[5] GBP inflated to 2021 prices using Bank of England calculator then converted to NZD at average 2021 rate of 1.9516

6.7.6 Direct Costs to Water Supplier

Direct costs to supplier were estimated based on lost revenue from supplying less water. Most of Wellington Water's residential customers are not currently metered. However, in all scenarios water metering is installed before 2030 so metering in place for most of the planning period and these losses will be applied.

The current Wellington Water volumetric charge of $2.88 per m^3 was applied. A wastewater volumetric charge of $3.174 per m^3 was also applied based on current charges in Auckland, New Zealand (Watercare, 2021).

The reduction in water use per person, per day of restriction level was assumed based on Wellington Water's drought management plan. A triangular distribution was applied to capture the range of possible values considering whether Level 3 restrictions reduce water use by 10% to 20%, with 15% as a midpoint.

6.8 Other Costs not Considered

6.8.1 Cultural Impact of Water Abstraction

Water has a significant cultural value to Māori, the indigenous people of New Zealand. These cultural values were not directly assessed due to the difficulty of doing so, and the overlap between cultural values and environmental values that were assessed.

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 (Māori people) including Te Mana o te Wai (the vital importance of water) which imposes a hierarchy of obligations that prioritises the health and well-being of water. Regional council's must give effect to Te Mana o te Wai in their freshwater management policy.

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 number of Māori proportional to the population (Resource Economics Ltd, 2020). 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, as well as further studies surveying the views and WTP of Māori and non-Māori in a drought event.

Increase in minimum residual flows over time

To align with Te mana o Te Wai, Wellington Water expects minimum flows in the Hutt River to be increased over time.

Cultural Values Associated with the Hutt River

A report assessing the impacts of increased temporary abstraction in the Hutt River identified cultural values that correspond closely to the environmental impacts that have been assessed (Raukura Consultants, 2008). Values included:

- Change in water quality;
- Recreational use such as swimming, canoeing and fishing; and
- Highlighting the importance of allowing flood flows to flow through unattenuated after periods of low flow to allow algae growth to be flushed.

The Hutt River has considerable cultural importance to local iwi due to its historical importance as a means of transport inland and as a source of food such as birds and eels. No Cultural Health Index assessment was carried out at the site but a high level review indicated the site would likely rate highly in such an assessment.

Due to the similarity of environmental and cultural values, it was considered reasonable to assess both within the estimated environmental value. A wide range of values are considered in the sensitivity analysis of environmental costs, including a high upper limit to account for the difficulty in accurately quantifying these values.

6.8.2 Political and Reputation Impact

The reputation and political impacts of drought are not considered. These may be more significant than the economic costs, especially if a drought is perceived to be due to mismanagement of the water supplier.

The emergency supply options of taking additional flow from the Hutt River and transporting water by water tanker from around the region by may have a large reputational cost that is not captured within the economic cost estimated in this study. Trucking water from neighbouring regions may have a large political impact even if the volumes being taken are relatively small. For example, there was significant media attention to importing emergency water by ship as part of the 2007/08 drought in Barcelona, despite this making up a very small (<1%) portion of total drought costs (Martin-Ortega et al., 2012).

It may be possible to estimate the political and reputational impact of droughts by estimating the cost fast-tracking capital projects that would not have occurred otherwise or the cost of supplier reforms in the face of perceived management failure.

6.8.3 Other Direct Costs to Water Supplier

Other possible direct costs to the water supplier that were not considered include fines for breaching limits from water takes, advertising campaigns to encourage water conservation and costs associated with inefficiency of accelerating capital spending on new water sources. The maximum fine for breaching abstraction consent conditions under current regulations is $600,000 which was not considered significant compared to other drought costs (Resource Management Act 1991, s339). Similarly, advertising campaigns were considered to be relatively low cost compared to the other drought costs so were not included.

It was considered unlikely that significant spending on new water sources would occur during the drought period given the short duration of a severe droughts in Wellington.

6.9 Results

Figure 22 and Figure 23 show the results from the severe restriction approach and the emergency water supply approach respectively. Figure 24 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 22: Results for severe restriction approach. Box and whisker plot of optimal level of service (minimum total cost) is overlaid

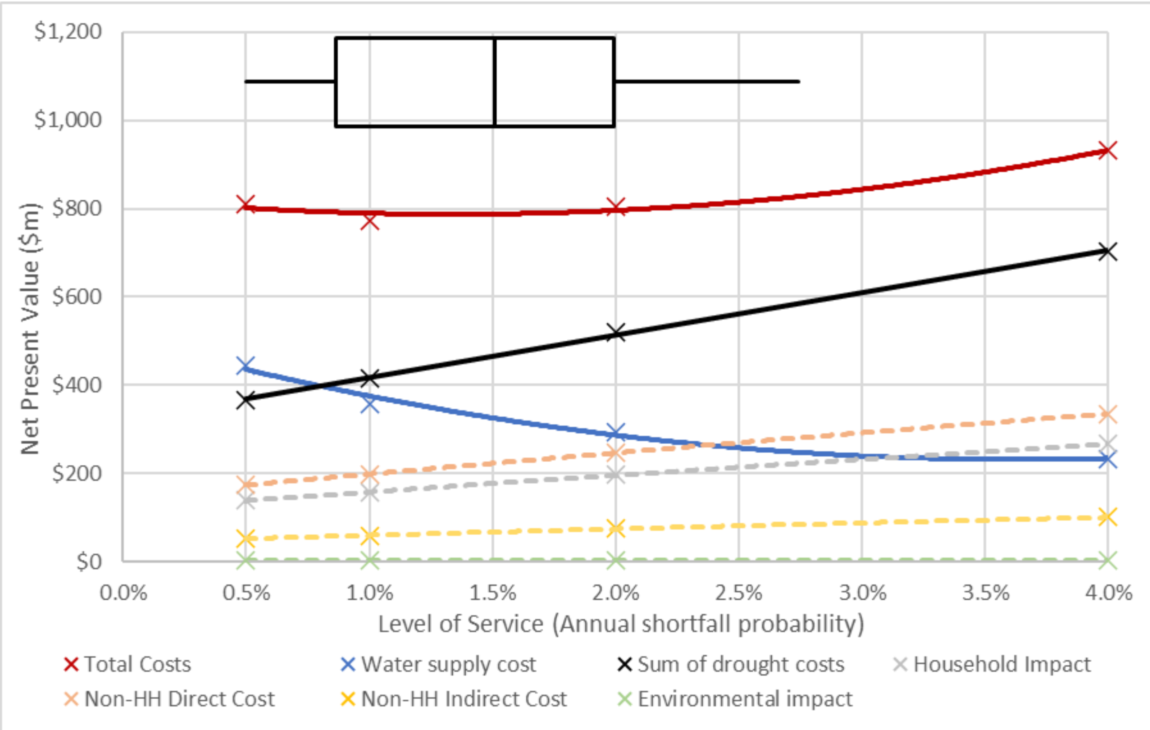


Figure 23: Results for emergency supply approach. Box and whisker plot of optimal level of service (minimum total cost) is overlaid

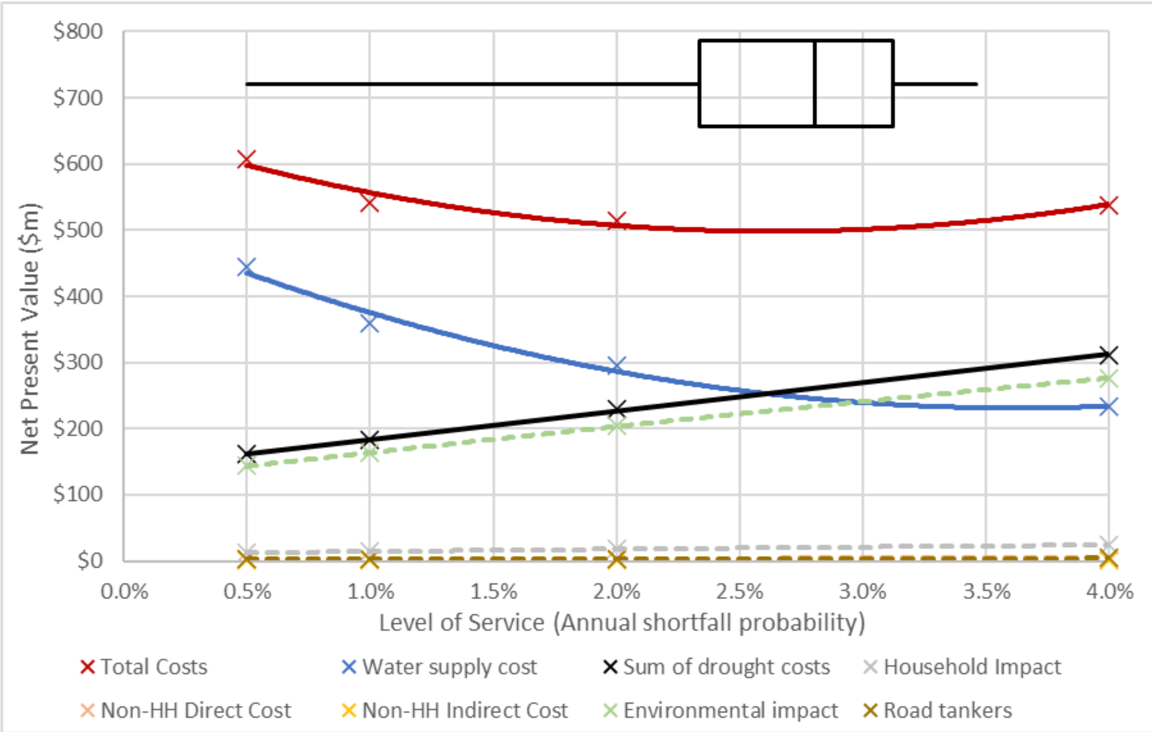
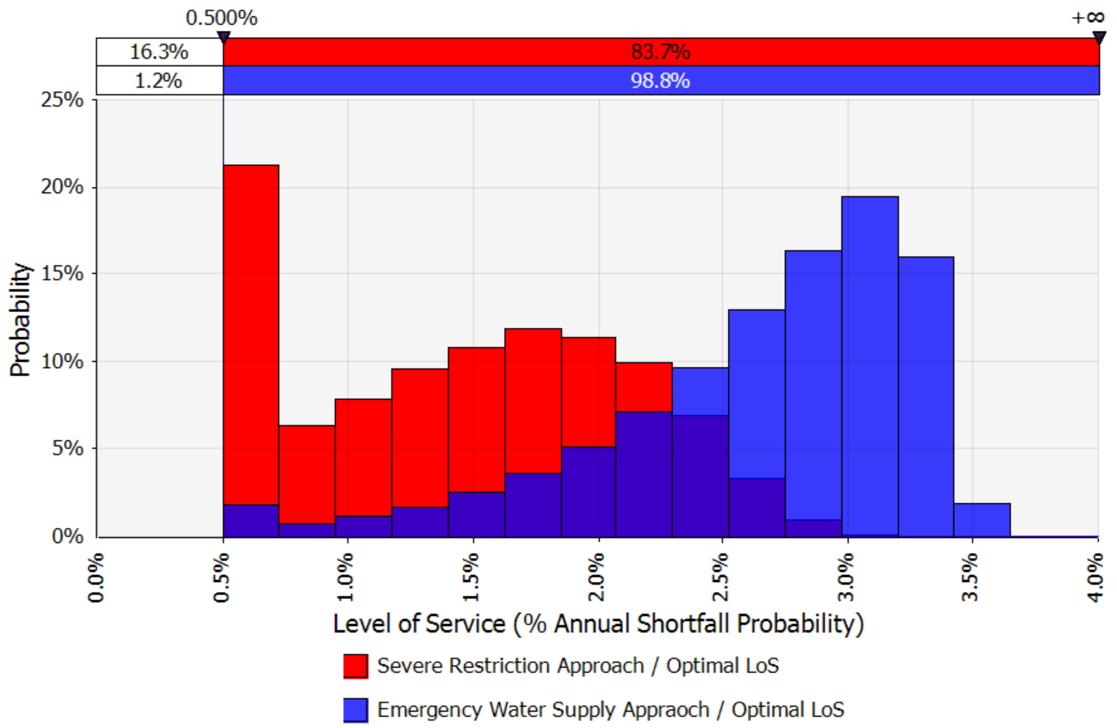


Figure 24: Optimal level of service results from Monte Carlo simulation for both severe restriction and emergency water supply approach



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 (Water UK, 2016), or through emergency water sources (National Infrastructure Commission, 2018), have indicated the need for significantly improving up to a 0.2%/1 in 500 year level of service.

There are a variety of reasons for results differing from the UK studies. A key difference is that drought costs are estimated per household per day. Wellington drought events will be short duration so of lower cost. The population of the Wellington region is relatively low so there may be higher water supply costs per capita for water supply.

Some assumptions may result in drought costs being underestimated which would result in the optimal LoS being underestimated i.e. the result should indicate a higher level of resilience. Such assumptions include:

- The true environmental costs may not be fully understood and captured. There were significant uncertainties in understanding and quantifying the environmental impacts.

- 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.

- 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 that were not costed.

Another key limitation of the study was that uncertainties in Wellington Water's system performance data were not considered. Ideally a range of plausible modelling scenarios would be tested over the planning period.

Finding Minimum Level of Service

The optimal level of service was estimated by fitting a second order polynomial through the total cost data points and finding the minimum of the curve. This approach appears appropriate for finding the optimal level of service where the minimum value within the middle of the range of LoS values from 0.5% to 4.0%. However, as the minimum value approaches the 0.5% margin, issues arise due to trying to fit a curve without values between 0% and 0.5% LoS. Total cost would be expected to increase exponentially as LoS approaches 0%. As a result, the predicted minimum LoS is likely overestimated where it is close to 0.5%.

This does not change the overall trend of results, and the median values for both the emergency supply and the severe restriction approaches are within the middle of 0.5% to 4.0% range of values.

6.10 Sensitivity Analysis

Monte Carlo Analysis

The Monte Carlo simulation approach allows identification of the inputs that the final LoS results were most sensitive to. Figure 25 and Figure 26 show tornado graphs for the results from the severe restriction approach and the emergency supply approach respectively.

The tornado graphs show the range of possible impacts on LoS if only a single input is changed, and all other inputs are kept constant. The range represents the impact from the 5^{th} to the 95^{th} percentile values from each input. Inputs are ranking in order from those the LoS is most sensitive to.

Figure 25 shows the inputs that have the greatest impact on LoS can be categorised into the impacts of Level 4 restrictions on households and businesses, and water supply investment costs, both capex and opex. The costs of Level 3 restrictions had minimal impact.

It is notable that optimal LoS results were similarly sensitive to water supply investment costs as to drought costs. Investing in improving confidence in water supply costs may be an efficient way for a supplier to increase confidence in optimal level of service depending on the current level of investigation and design in future water supply infrastructure.

Average duration of Level 4 restrictions also had a significant impact on the optimal LoS result which is understandable given costs are expressed per day of restriction level.

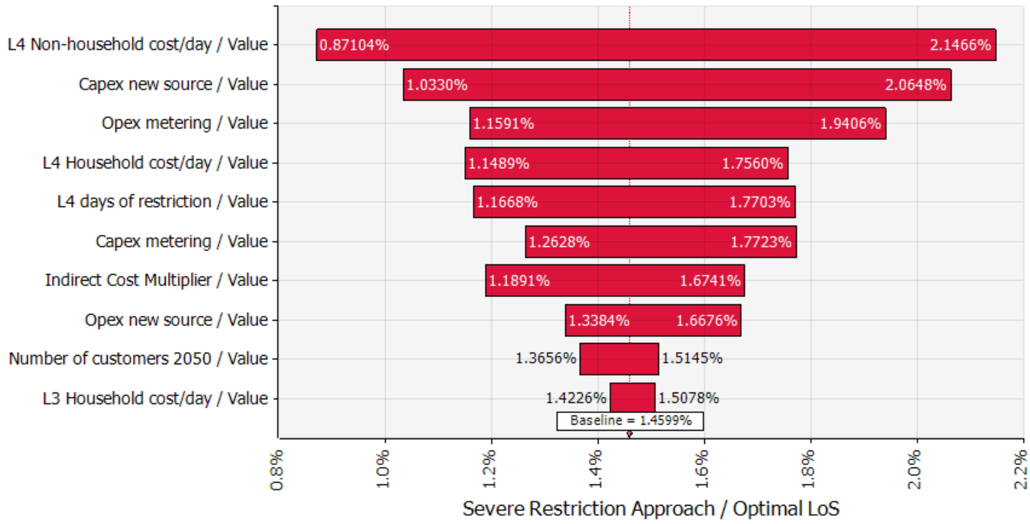


Figure 25. Tornado graph for the severe restriction approach

Figure 26 shows that percentage change in environmental values from abstraction is the input that has the largest impact on optimal LoS. This can be attributed to the significant uncertainty in linking abstraction with environmental outcomes, and because total drought costs are dominated by environmental costs rather than being split between several types of drought cost.

The sensitivity analysis displays how important it is to improve understanding of the impact of significant abstraction on environmental values for the specific waterways where water is taken as this has a very significant impact on optimal LoS.

Results are also relatively sensitive to costs per change in ecological indicators and human health risk as well as capex and opex costs of water supply investments.

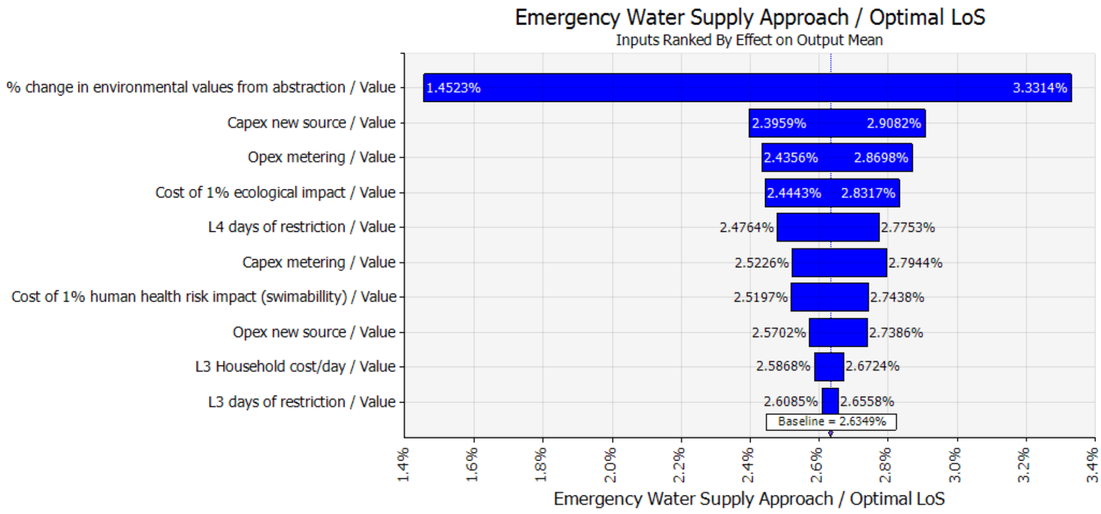


Figure 26. Tornado graph for the emergency supply approach

Discount Rate

A 2% discount rate was tested as an alternative to the 5% discount rate for water infrastructure recommended by The New Zealand Treasury (2020). Testing sensitivity to discount rate with an alternative 2% discount rate is proposed by the New Zealand Treasury (2021).

Table 15 shows the optimal LoS results for both the severe restriction approach and emergency water supply approach at 2% and 5% discount rates. Sensitivity to discount rate is similar in magnitude to some of the key inputs shown in the tornado graphs in Figure 25 and Figure 26. Sensitivity to discount rate is to be expected as capital water supply infrastructure costs are paid upfront whereas the benefits of reduced drought risk accrue over time.

Table 15. Sensitivity of Optimal LoS to discount rate

Discount Rate	Severe Restriction Approach – Optimal LoS	Emergency water supply approach – Optimal LoS
5%	1.5%	2.8%
2%	0.5%*	2.3%

0.5%* indicates an optimal level between 0% and 0.5% as 0.5% is the lower bound of values tested.

The results indicate that the severe restriction approach is more sensitive to discount rate than the emergency supply approach. This is because the severe restriction approach estimated higher drought costs so will be affected more by discounting these costs. Water supply costs in both approaches are the same so will be affected identically by changes in discount rate.

6.11 Conclusion

The purpose of this case study was to test the framework developed in Chapter 5 and to test a selection of methods for estimating the various relevant drought costs discussed in Chapter 4. The practical application of these methods highlighted challenges that a water supplier may face in estimating the cost of drought to inform water supply investment decision making.

The framework proposed in Chapter 5 was successfully applied to Wellington Water's modelling data. A key assumption of the framework was to model drought costs as cost per restriction level per day which was mostly successful in simplifying the link between drought cost and water system modelling.

The values applied to the case study were generally restricted to transfer from other primary studies due to time and resource constraints. Therefore, many of the challenges identified were associated with the transfer of values and the differences between the original study location and Wellington.

Severe Restriction Approach

The cost per restriction level per day assumption was most successful for the severe restriction approach where costs are much more clearly linked to the levels of restrictions imposed by the supplier. Cost per day is appropriate as drought impacts will only last as long as the duration of the restrictions.

The drought cost per day was assumed to be constant regardless of the duration of restrictions. This may not be appropriate, as discussed in Chapter 4. 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, representing the shock of having water shut off, increasing the average cost per day for shorter duration droughts. A similar relationship could be expected for non-household direct costs.

A possible improvement to the framework would be to adjust the cost format to allow a lump sum cost representing the aversion of severe restrictions of any duration, plus a cost per day as before.

The case study highlights the challenge of transferring primary studies from other locations to the area of interest. Variations between sites, in this case the difference in drought duration (three months in the primary study compared to three weeks in Wellington) lower confidence in the final costs. The relatively low number of primary studies into willingness to pay to avoid water restrictions, and the lack of New Zealand studies, limit confidence in the final results without performing an original primary study.

Emergency Water Supply Approach

The case study illustrates the significant challenge in quantifying the environmental costs associated with the taking water beyond environmental limits. There are two layers of uncertainty. First, the environmental impacts of taking water beyond minimum environmental flows need to be estimated. Then the monetary value of the impacts 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.

The Hutt River is relatively well studied with recent studies into the impacts of abstraction as well as river ecology and cynobacteria (algae) blooms. It would be even more challenging for waterways that had not been as well researched.

This illustrates the difficulty of estimating environmental impacts of extreme events, even where there have been studies on abstraction from the specific river. There are complex interactions of flow, temperature and water chemistry that could have unforeseen effects when taking beyond minimum environmental flows.

The case study showed that the emergency supply options can be very location specific. The short duration of droughts in Wellington limits the emergency supply options that are feasible. The isolated location of New Zealand also limits feasible options as water tanker ships or temporary desalination plants would take much longer to arrive.

Further Research

The sensitivity analysis highlighted areas where further research would have the largest benefit in estimating Level of Service for water supply for Wellington Water.

The first area is to better understand the long-term impacts of short-term abstraction beyond environmental limits in the Hutt River and the rivers and stream that supply the Wainuiomata treatment plant. The resources to complete such as study may not be prohibitive as they would be an extension of existing studies into abstraction from these waterways. This would be novel research as recovery of ecosystems from the low flows of drought is not a very well researched area (DEFRA, 2013).

Another challenge is to link environmental impacts to household's WTP to avoid them. The existing Resource Economics Ltd (2020) study that was applied focusses on WTP to improve waterway health by permanently reducing agricultural impacts in the long term, which may differ from the shorter term impacts of water abstraction. A primary study into household WTP in the Hutt River would require significant resources but would allow much more confidence in the results.

The second area of further study would be a primary study into household and business willingness to pay to avoid restrictions. Such as study could be structured to be used not just in Wellington but by suppliers throughout New Zealand. A primary stated preference study requires significant resources but could be justified by the billions of dollars that will be spent on water infrastructure in New Zealand over the coming decades.

The final area of further study which is investigating future water supply investment options to allow capex and opex cost estimates to be tightened. This study is already underway.

Policy Implications

A key policy implication for Wellington Water is that 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 preserve water in the storage lakes and lower the risk of more severe household or environmental impacts.

Road tankering was found to be a relatively low-cost emergency supply option, albeit with low capacity. Making preparations prior to a drought would be sensible given the short lead in times to drought events in Wellington. Preparations would include entering agreements to take surface water from neighbouring councils, agreements with water tanker or milk tanker companies to utilise their equipment in an emergency and installing any equipment necessary at the tanker discharge location at Macaskill Lakes to ensure multiple tankers can discharge simultaneously.

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 by current and future generations at current levels of service. Further research that improves the understanding of relative costs and community preferences will help suppliers to make better informed decisions during a drought, as well as giving greater certainty to the optimal level of service of Wellington Water's supply network.

Finally, it is important to highlight that Wellington Water's drought plan outlines that for Level 4 restrictions a 35% reduction in total demand is expected but it does not specify how those reductions will be produced. The drought plan does not explicitly state when the options in this case study would be applied - temporarily lowering the Hutt River or of cutting off water to some customers. It is possible that expressly articulating these options was avoided because of the risk of negative political reactions to the proposal even though, as outlined above, the environmental impacts may be cost-effective compared to increasing water supply investment. The explicit option of lowering the Hutt River in the drought plan or of implementing restrictions that cut off supply to some customers may be useful in not only correctly identifying the nature of the drought risk and currently available response measures but also in justifying local and central government investment in improving the Wellington water supply infrastructure. The goal of this research overall is to emphasise the importance of understanding the current cost of drought in order to accurately assess the relative cost of network investments. Greater detail and specification of the available drought measures in drought plans is a first step towards this objective.

Drought management plans should clearly define who (households and non-household users) will be affected at each restriction level and the extent they will be affected. This allows more accurate modelling of the costs of drought and allows trade-offs between policy options to be compared. Making drought management plans open and transparent allows for open and honest consultation with the community. It is ultimately the community who will be affected by restrictions. Without a clear and open drought plan, a supplier may be more susceptible to pressure from competing groups and may end making suboptimal decisions.

CHAPTER 7 CONCLUSIONS

This section offers conclusions in relation to three main research objectives of this study:

- Assessing methods for estimating drought costs in urban areas;
- Developing a framework for integrating the cost of drought in water supply planning in urban areas; and
- Applying the framework and a variety of methods for assessing drought costs in a case study with a New Zealand urban water supplier.

7.1 Assessing Methods for Estimating Drought Costs

Drought impacts urban areas in multiple ways causing a range of different costs. The full range of these drought costs – direct, indirect and non-market – need to be estimated. An under or over-estimation of drought costs could have significant ramifications for network planning decisions.

This research assessed a range of methods suitable for estimating drought costs in urban areas. Previous assessments of methods for assessing drought costs were from economics literature and had some gaps that were addressed in this research. The novel aspects of this research include:

- A focus on drought costs in urban areas. Previous research tended to focus on agricultural drought costs.
- An interdisciplinary approach, notably the inclusion of methods from both economics literature and practical but less robust methods from water industry studies.
- This study gives detailed and practical consideration of how methods could be integrated by suppliers within their water supply planning, a user-focussed approach that takes the research one step further than existing studies.

Methods where this research provided specific, novel insights to existing literature include:

- An assessment of methods that estimate the impact of water shortages on GDP per sector. These methods had been applied in water industry studies but had not been assessed in economics literature. This research provided practical guidance about several challenges a water supplier may face in implementing these methods in urban areas.

- There is far more diversity in the types of sectors and industries in urban areas compared to agricultural areas. There has been surprisingly little research on the impacts of drought on urban businesses – despite the majority of economic output being generated in urban areas.

- Economics literature recommends input-output or computational general equilibrium methods as the most comprehensive methods for assessing indirect drought costs. This research found it difficult to justify the high resource requirements needed for these methods in urban areas. A simpler economic amplification ratio approach may be more suitable.

- Non-market costs are considered the most difficult drought costs to estimate and are often excluded from estimates of drought for this reason. This research provides specific practical guidance for estimating the two key non-market costs: the impact of water restrictions on households and the environmental costs of water abstraction. The format of results of studies is a particular focus to enable studies to be easily integrated within water supply planning. The focus on easily translatable results is consistent with the pragmatic concern throughout this research that assessment of costs are able to be applied by suppliers.

- Stated preference methods are generally seen as of secondary utility compared to methods based non observable market data. However, stated preference methods may be particularly suitable for estimating the direct costs of drought on businesses in urban areas due the diverse range of industries in urban areas and the ability of such entities to quantify their willingness to pay in terms of the profits they stand to lose from water restrictions.

7.2 Framework for Integrating the Cost of Drought in Water

This study presents a practical framework for water suppliers to integrate the costs of drought in water supply planning. The framework accounts for the unique characteristics of droughts in urban areas, including how a water supplier will react and apply increasingly severe restrictions during a drought event. A unique feature of the framework is utilising the costs of drought to assess trade-offs between different drought management strategies.

The framework also considers integrating drought costs into the long term water supply planning, considering both conventional and more modern water supply planning approaches.

7.3 Case study with New Zealand Water Supplier

7.3.1 Overview

A selection of methods for estimating the various relevant drought costs discussed in Chapter 4 and the framework proposed in Chapter 5 were successfully applied to the New Zealand water supplier Wellington Water's network modelling data. The practical application of these methods and the framework highlighted challenges that a water supplier may face in estimating the cost of drought to inform water supply investment decision making.

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 illustrated the difficult choice a supplier may face during a severe drought, selecting between the drought management strategies of severe restrictions where water is cut off for some customers or taking emergency water beyond environmental limits, with high environmental costs. The comparison of these two different drought management options demonstrates the novel approach proposed in Chapter 5 to use drought costs to compare short term drought management options.

The results indicate that, in the case of Wellington Water, taking water beyond environmental limits likely has lower economic costs than severe restrictions, however the research identifies several challenges and uncertainties in linking river abstraction with environmental costs.

7.3.2 Severe restriction approach

The severe restriction approach assumed that in a severe drought, Wellington Water would impose rotating water cuts to sections of the network. The most significant costs under this approach would be the non-market impacts on households and direct costs to non-household (business, industry, public sector) users.

This is an opportunity for further research through a primary study into New Zealand urban household and business willingness to pay to avoid water restrictions as none currently exist. Such a study could be structured to be used not just in Wellington but by suppliers throughout New Zealand. A primary stated preference study requires significant resources but could be justified by the billions of dollars that will be spent on water infrastructure in New Zealand over the coming decades.

A core assumption of the Chapter 5 framework was that drought costs can be expressed in cost per restriction level per day which worked well under the severe restriction approach. Although some questions were raised about the non-linear relationship between customer willingness to pay per day and drought duration.

The sensitivity analysis highlighted that the optimal level of service was similarly sensitive to the Capex and Opex water supply investment costs as to drought costs. Investing in improving confidence in water supply costs may be an efficient way for a supplier to increase confidence in optimal level of service.

7.3.3 Emergency water supply approach

Options for emergency water supply in Wellington are limited by the short duration of drought events. Abstraction from the Hutt River beyond minimum residual flows was identified as the only feasible emergency supply option that could provide significant emergency water supply.

The case study illustrates the significant challenge in quantifying the environmental costs associated with the taking water beyond environmental limits, despite the Hutt River being relatively well studied. 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.

There is an opportunity for further study to understand the long-term impacts of short-term abstraction beyond environmental limits in the Hutt River and other river and stream sources in the Wellington region. This would be novel research as recovery of ecosystems from the low flows of drought is not a very well researched area (DEFRA, 2013).

Another opportunity for future research is a primary study into household willingness to pay to avoid degradation in the Hutt River from water abstraction. Existing New Zealand studies focus on activities that will have long term impacts on waterway health, such as fencing off livestock, which may differ from the shorter term impacts of water abstraction.

7.3.4 Supplier Policy

A key policy implication for Wellington Water is that the cost of lower level restrictions is low and environmental impacts from taking some additional flow from the Hutt River are low. Taking these measures early in a drought may be prudent to preserve water in the storage lakes and lower the risk of more severe household or environmental impacts.

For more severe droughts, an improved understanding of the relative costs of severe water restrictions and takes from Hutt River beyond environmental limits would help Wellington Water justify difficult decisions between these drought management options.

Finally, assessing the cost of drought will become more important to water suppliers and communities as climate change increases the frequency of drought events. Significant sums will need to be spent on water infrastructure, and this investment will need to be justified by the counterfactual of drought costs. This research advances such network planning by assessing the different methods for assessing drought costs and enabling the trade-offs to be compared and assessed.

To this end, a drought plan should explicitly mention the steps the supplier may have to take for emergency supply or restriction policy. Expressly acknowledging the possible actions that a supplier may be required to take would not only increase understanding of the likelihood of drought events and the current state of the network and supply, but also prepare the public for realistic consequences in a severe drought event (thereby possibly lowering future political costs). Crucially, a clear drought plan that highlights the true potential drought costs could be integrated within network modelling to inform the optimal level of investment in network infrastructure that will only continue to grow in importance.

Appendix A - Assumptions from Wellington Water modelling

Table 16. Assumptions from Wellington Water modelling

Category	**Assumption**	**Lower estimate**	**Expected value**	**Upper Estimate**	**Distribution**	**Source**
Costs of improving water supply	Capex new source 1 (metering)	$54,329,500	$108,659,000	$217,318,000	Weibul (minimum set at 5% value, expected at 50% value, upper at 95% values)	Expected value: Ernst & Young (2020) Distribution: own assumption
	Opex new source 1 (metering)	$4,155,000	$8,310,000	$16,620,000		
	Capex new source 2	$125,000,000	$250,000,000	$500,000,000		
	Opex new source 2	$1,750,000	$3,500,000	$7,000,000		
Population growth	Wellington water customers 2050	560,000	580,000	600,000	Triangular	Expected value: Ernst & Young (2020) Distribution: own assumption
Average length of restriction	Average length of Level 3 restrictions	20	30	40	Triangular	Own assumption based on discussion with Wellington Water and Williams (2019)
	Average length of Level 4 restrictions	15	20	25	Triangular	

Category	Assumption	Lower estimate	Expected value	Upper Estimate	Distribution	Source
Discount Rate	Discount rate for water infrastructure	2%	5%			The New Zealand Treasury (2020) A sensitivity check at 2% suggested by Treasury (2021)

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