WATER SERVICES
ASSOCIATION OF AUSTRALIA

Urban Water Resources Planning Framework

Guideline

March 2024

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For more information

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About WSAA

The Water Services Association of Australia (WSAA) is the peak body that connects the Australian urban water industry, representing over 70 public and privately owned water or water related organisations. Our members provide water and wastewater services to over 20 million customers in Australia and New Zealand.

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UN Sustainable Development Goals

Project outcomes contribute to the following UN Sustainable Development Goals:

- 3 GOOD HEALTH AND WELL-BEING
- 6 CLEAN WATER AND SANITATION
- 7 AFFORDABLE AND CLEAN ENERGY
- 8 DECENT WORK AND ECONOMIC GROWTH
- 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
- 11 SUSTAINABLE CITIES AND COMMUNITIES
- 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
- 14 LIFE BELOW WATER
- 15 LIFE ON LAND
- 17 PARTNERSHIPS FOR THE GOALS

For more information about the water industry's contribution see Global Goals for Local Communities: Urban water advancing the UN Sustainable Development Goals.

URBAN WATER RESOURCES PLANNING FRAMEWORK
SUMMARY

This urban water resources planning framework (the Framework) brings together ***contemporary good practice principles for urban water resources*** planning from water service providers across Australia and New Zealand.

What is good practice urban water resources planning?

Urban water resources planning involves balancing supply and demand for water for towns and cities over the long-term. This occurs at a level of service that is agreed with the community and/or government, in the context of broader community objectives for liveability, sustainability, and value for money. This level of service includes maintaining a minimum water supply to sustain life (i.e. water for drinking, cooking, and sanitation), and for essential services and industries. It also includes providing water for all uses at an agreed performance standard.

Balancing supply and demand can be challenging due to uncertainty in future water availability and demand. This uncertainty stems from factors that include climate variability and climate change, changes in population and individual water use over time, and changes in the regulations that govern water availability.

Good practice planning embraces uncertainty by using risk-based decision making that values supply system robustness (i.e. the ability to withstand change) and adaptability (i.e. the ability to adapt in response to that change), which leads to resilience (i.e. the ability to recover from change). Good practice planning is timely, consultative, evidence-based, holistic, and transparent, with a long-term view in mind.

Who is the Framework for?

The Framework is targeted at urban water resource planners and their government counterparts.However, the information presented is broadly relevant to anyone engaging in urban water resource planning or associated decision making. This Framework replaces the earlier *Framework for Urban Water Resource Planning – WSAA Occasional Paper No. 14* (Erlanger and Neal, 2005).

When to use the Framework?

The Framework complements existing guidance, and also aims to support urban water resource planners operating in jurisdictions which do not have such guidance. Planners should always apply their local urban water resources planning guidance first, where available. The Framework can then be drawn upon for additional support if needed.

The Framework provides a starting point for exploring concepts of interest in more detail through the commentary and references provided. Planners should engage with their colleagues, customers, and other stakeholders to decide how best to apply these concepts to a local water supply system.

Good practice urban water resources planning is continually evolving. In addition to using the Framework, it is important that planners keep up to date with new ideas and case study applications through water industry participation.

What is in the Framework?

The Framework is designed to allow planners to read it in its entirety, or to dive into particular topics of interest where further guidance is sought. It includes:

- **An overview of urban water resources planning** – what it is, why it is important, and what the challenges and opportunities are that it addresses.
- **Planning principles**, including a discussion of each principle and references to further reading. A principles-based approach was adopted for the Framework to enable it to complement local guidance, and to encourage reflection on current practices without stifling innovation. A principles-based approach was considered to generate more accessible and digestible guidance than a detailed how-to manual, whilst also ensuring a longer shelf-life for the guidance.Over-arching principles include that water resources planning:
    i. Is not undertaken in haste or in response to a crisis, but rather involves careful consideration and consultation, with a long-term, whole of system view in mind;
    ii. Is holistic and integrated, including consideration of both drinking water and other fit-for purpose water sources (including recycling), at various scales, to meet a broad range of community objectives;
    iii. Warrants a higher level of effort and investment when water resource risks for a supply system are higher; and
    iv. Is cyclic and ongoing, including plan development, implementation, monitoring, adaptation, reflection, and renewal.

More detailed planning principles are categorised under the following themes:

- **Understanding your current supply system:** current water use and system operation, current water availability and non-stationarity, climate independent water sources, fit-for-purpose water use, climate variability, water resource planning models, stochastic data, optimisation, and data availability and quality.
- **Understanding your water supply needs:** performance metrics and standards, including community input to those metrics and standards.
- **Future demand and water availability:** future water use, climate change impact assessment, risks for shared water resources, risks to water supply from bushfires, and changes in runoff and recharge during and after extended drought.
- **Decision making:** future uncertainty, robustness and resilience, planning approaches to support decision making, decision making, drought planning links, supply system shocks, and supply system contingencies.

The Framework also includes:

- **A self-assessment checklist** a series of yes/no questions to check what has been considered in your planning process.
- **Future research and investigation priorities** to support future improvements in urban water resources planning.
- **A glossary** of terms recommended, and suggested terms to avoid.

What are the benefits of using the Framework?

Benefits of good practice urban water resources planning include better investment decisions, greater community ownership and support for those investments, greater certainty for water users, and lower levels of stress for the community. Importantly, good practice planning helps to avoid the potentially dire consequences of no longer being able to supply water. For further information about the Framework, and to obtain a copy, visit the Water Services Association of Australia website (https://www.wsaa.asn.au/).

TABLE OF CONTENTS

1. INTRODUCTION

Water service providers are responsible for providing a safe and reliable water supply to their customers, both now and into the future. It is expected that water service providers manage their water resources so that communities never run out of water for their essential needs. Beyond this minimum requirement, there is an expectation that urban water resources are prudently planned for and managed at an agreed level of service for all other water uses.

Prudent water resources planning recognises the inherent uncertainties in future water availability and demand. It supports risk-based decision making that values robustness and adaptive planning in the face of uncertainty, whilst balancing community expectations for reliability of supply against the cost of providing that supply. It also seeks to support and enhance broader community benefits.

1.1 About the Framework

This urban water resources planning framework (the Framework) consolidates contemporary good practice principles for urban water resources planning from WSAA member representatives in Australia and New Zealand. The Framework supports continuous improvement as part of good practice planning.

The Framework is not an industry standard or how-to manual. It is intended to serve as a reference document to support urban water resource planning and replaces the earlier *Framework for Urban Water Resource Planning – WSAA Occasional Paper No. 14* (Erlanger and Neal, 2005).

The target audiences are water resource planners and their government counterparts. However, the information presented is broadly relevant to anyone engaging in urban water resource planning or associated decision making.

1.2 When to use the Framework

The principles presented in the Framework aim to complement existing guidance and to support water service providers operating in jurisdictions which do not have specific urban water resource planning guidance (Figure 1). Water service providers should always meet any obligations or expectations to use local urban water resources planning guidance first. They can then draw upon the Framework when looking for additional support.

The knowledge presented in the Framework provides a starting point for exploring concepts of interest in more detail, through the references provided and the reader's own independent research. Readers will still need to engage with their colleagues, customers and other stakeholders to decide how best to apply these principles to a local water supply system. In some parts of the Framework, approaches and assumptions are suggested which align with these principles, recognising that different approaches and assumptions can often be used.

Good practice urban water resources planning is continually evolving. In addition to using this guidance, it is important to keep up to date with new ideas and case study applications through water industry participation.

1. Use your local guidance first

If urban water resources planning approaches have already been specified in your jurisdiction, make sure you are meeting any obligations or expectations for planning that are placed on your organization.

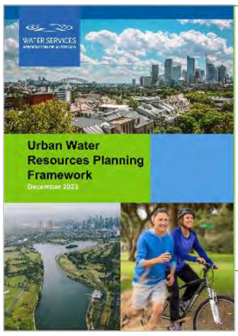
2. Draw on this guidance

To add to your knowledge of good practice principles:

a) **For water service providers:** to support your planning, particularly when local guidance is not available or not fully meeting your needs

b) **For government:** When developing or updating your own guidance or regulation

This framework is:



- Water service provider focused
- Informed by WSAA member experience and knowledge
- Principles-based, so it is not a detailed how-to manual

3. Explore the references provided for more information, **discuss** the principles amongst your colleagues and with your stakeholders, and **keep up to date** with emerging knowledge and techniques through industry participation

Figure 1 When to use the Framework

1.3 The Framework

The Framework itself can be navigated using Figure 2. It includes background information on the urban water resources planning process in Section 2, followed by more detailed discussion of specialist topic areas (Section 3 to 7). The specialist topic areas are thematically structured based on understanding:

1. your current supply system behaviour;
2. your water supply needs and obligations; and
3. projected future water resource and demand conditions.

This is followed by approaches to turn that knowledge into decision making, during:

4. plan development; and
5. implementation of your planned actions.

A self-assessment checklist for water service providers undertaking urban water resource planning is also provided (Section 8). Discussion of the specialist topic areas with water service providers generated priority topics for future research and investigation to support improved urban water resources planning (Section 9). A glossary of key terms is included in Section 10.

Principles located throughout the Framework are highlighted in tables formatted as per Table 1 to make them easier to find.

Table 1 Water resource planning principle tables

Title	Principle
PP-1: Planning principle tables	Important planning principles within the Framework are presented in tables like this one to make them easier to find and consider.

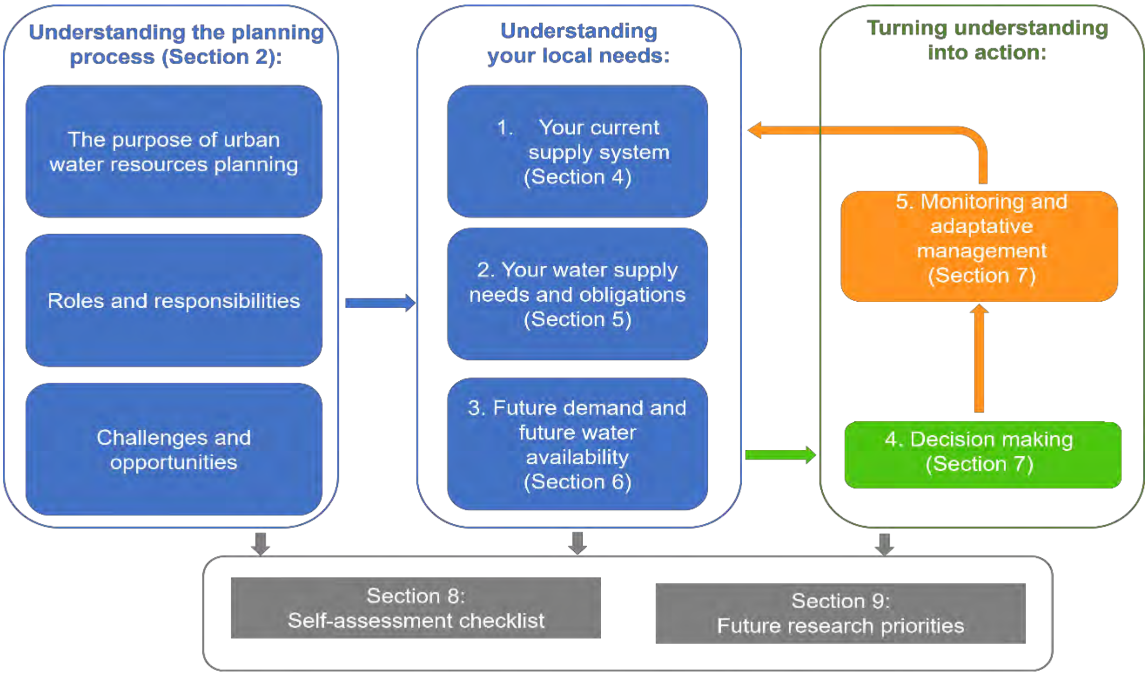


Figure 2 The urban water resources planning framework (the Framework)

1.4 Other guidance

The Framework does not exist in isolation. It is supported by other WSAA guidance on related topics and will provide support to the development of related future guidance and advice to government (Figure 3). The Framework has also drawn upon existing urban water resource planning advice from State and federal governments and from international guidance. The development of the Framework involved exploring the different approaches that have been adopted, whilst recognising the differences in intended audience for some of that existing advice.

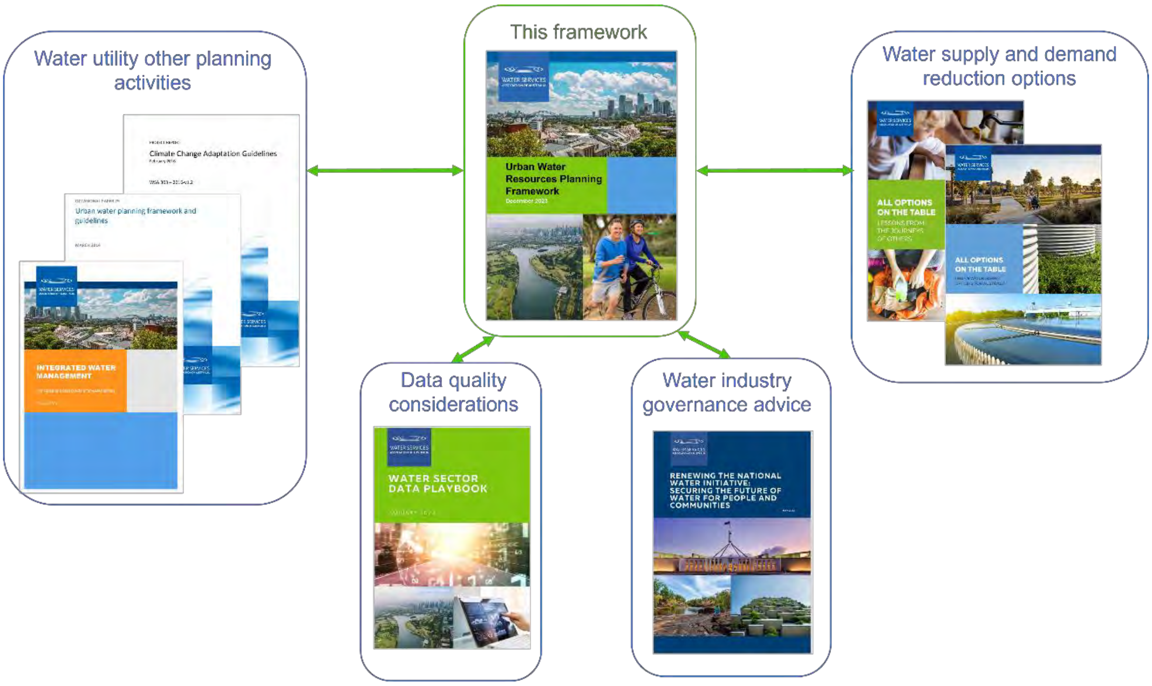


Figure 3 The Framework and other WSAA guidance

Other guidance for water resources planning and climate change that was drawn upon when drafting the Framework included:

- Australian State Government urban water planning guidance in Victoria (DELWP, 2021), New South Wales (DPE, 2022), and Western Australia (WAPC, 2008; 2021);
- Australian State and Federal Government climate change guidance in New South Wales (https://www.climatechange.environment.nsw.gov.au/home), Victoria (DELWP, 2020), Western Australia (DWER, 2023), South Australia (DEW, 2022), and nationally (https://www.climatechangeinaustralia.gov.au/en/); and
- International urban water planning guidance for England and Wales (Environment Agency et al., 2023) and the United States (AWWA, undated).

2. URBAN WATER RESOURCES PLANNING

2.1 What is urban water resources planning?

Urban water resources planning involves balancing available water resources and the demand for those resources at an agreed level of service, over a planning horizon, whilst maintaining a minimum level of service to always meet critical human water needs[1]. This occurs in the context of broader community objectives for liveability, sustainability, and value for money. The planning horizon for urban water resources planning has a long-term view in mind, typically over several decades. Sustainability over the long-term supports inter-generational equity.

Urban water resources planning incorporates elements of drought planning and emergency management planning and is strongly intertwined with them. However, it differs from these planning activities because of the time frame available for decision making.

Table 2 Water resource planning principle for prudent planning

Title	Principle
RP-1: Prudent decisions are well planned	The most prudent urban water resources planning decisions are not made in haste in response to a crisis, but rather are the result of careful consideration and consultation, with a long-term view in mind.

Urban water resources planning is informed by operations and asset management, and informs asset planning, but is distinct from each of these activities. Urban water resources planning assumes that water quality will be fit-for-purpose, or adopts appropriate constraints where water quality may limit its use. It therefore needs to be integrated with source water quality planning and water treatment asset planning to ensure that any water quality constraints are well understood. Urban water resource planning has traditionally related to only the drinking water supply system. However it now involves applying the same planning concepts for meeting non-drinking water demands with fit-for-purpose water sources, which may not necessarily be of drinking water quality. Through this link, urban water resource planning interacts with wastewater planning, stormwater management, and integrated water management.

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[1] Refer to the glossary for any unfamiliar terms

Table 3 Water resource planning principle for holistic planning

Title	Principle
RP-2: Holistic planning	An integrated planning approach that considers drinking water supply as well as other fit-for-purpose water sources (at various scales), wastewater planning (including recycling), and broader community costs and benefits, can help identify additional opportunities and risks for urban water supply planning.

2.2 The importance of good practice planning

Good practice urban water resources planning is timely, well-considered, consultative, evidence-based, and transparent. Good practice urban water resources planning, which is consistent with the principles outlined in this Framework, has many benefits. Equally, not implementing good practice urban water resources planning can have negative consequences.

Benefits include:

- Better investment decisions with higher potential benefits and lower potential regret;
- Greater community ownership and support for those investment decisions, and greater community confidence in the water service provider's ability to manage their water supply system;
- The avoidance of bill shock associated with rushed implementation of higher cost water sources;
- The avoidance of the potentially dire consequences of no longer being able to supply critical human water needs;
- Greater social amenity for water dependent community assets, including more green spaces (e.g. parks, gardens, and sportsgrounds), more blue spaces (e.g. healthy wetlands, rivers, and creeks), and reduced urban heat;
- Better environmental outcomes;
- Greater certainty for businesses that require a reliable source of water; and
- Lower levels of stress for the community, and lower levels of workplace stress for water service provider staff and government regulators.

ISO 31000, defines risk as the effect of uncertainty on objectives (International Organisation for Standardization, 2018). Typically, it is characterised in terms of risk sources, potential events, their consequences, and their likelihood.

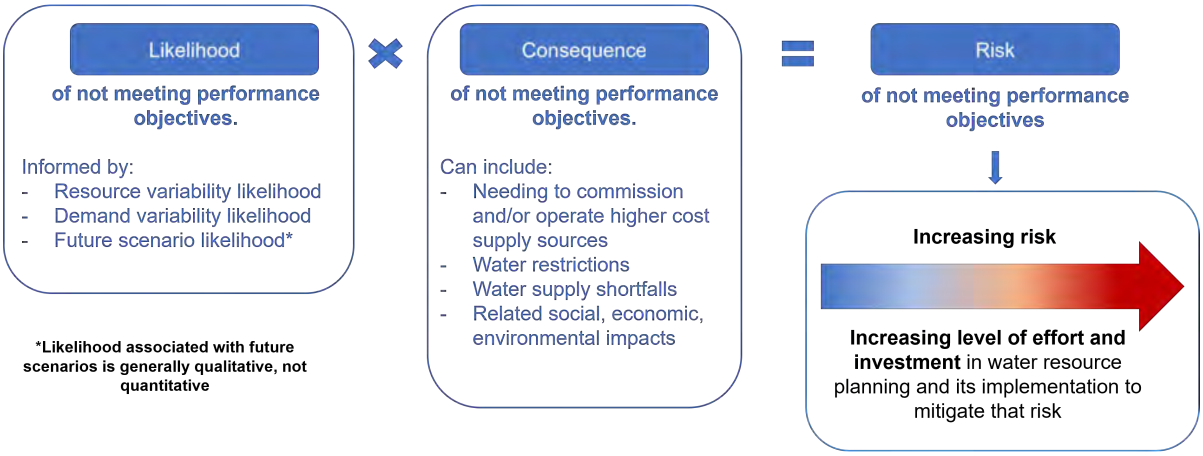
In the context of urban water resource planning, risk is typically expressed as the combined likelihood and consequence of not meeting performance objectives for the supply system. The most significant water resource planning risks are typically associated with low likelihood, high consequence events.

The appropriate level of effort to expend on urban water resources planning will depend on the level of risk that a supply system is facing, as shown in Figure 4.

Table 4 Water resource planning principle for the level of effort to expend on planning

Title	Principle
RP-3: Risk and level of effort	When water resource risks for a supply system are higher, the level of effort and investment in water resources planning, and its implementation to mitigate that risk, should be higher.

The likelihood of future scenarios (e.g. for climate change or population growth) will often not be known precisely, and there is a high degree of subjectivity in interpreting relative likelihoods and consequences. Different communities, different water service providers, and different government regulators will also have different risk appetites. For these reasons, the Framework does not prescribe a standardised risk matrix. However, the general rule remains that higher risk requires greater investment in urban water resources planning. Equally, a supply system facing very low risk would require a lower planning effort. This could occur, for example, because current performance exceeds expectations, demand growth is low, or its water sources have little or no dependence on climate. It could also occur because suitable low-cost contingency supply measures are readily available if needed.



*Likelihood associated with future scenarios is generally qualitative, not quantitative

Figure 4 Risk and level of effort and investment in urban water resources planning

2.3 Risk and levels of service

Water supply systems can be “gold plated” to avoid potential risks, however this often comes at a higher cost to customers due to greater investment in water resource infrastructure and operation. Similarly, lower investment in a water supply system can result in higher costs to customers, through periodic water restrictions and supply shortfalls (and their associated socio-economic costs). It can also result in the need to source emergency supplies at short notice, often at very high cost. This is illustrated conceptually in Figure 5, noting that different communities will each have a different appetite for risk. This reflects their different costs for sourcing more water and different levels of hardship when water cannot be provided.

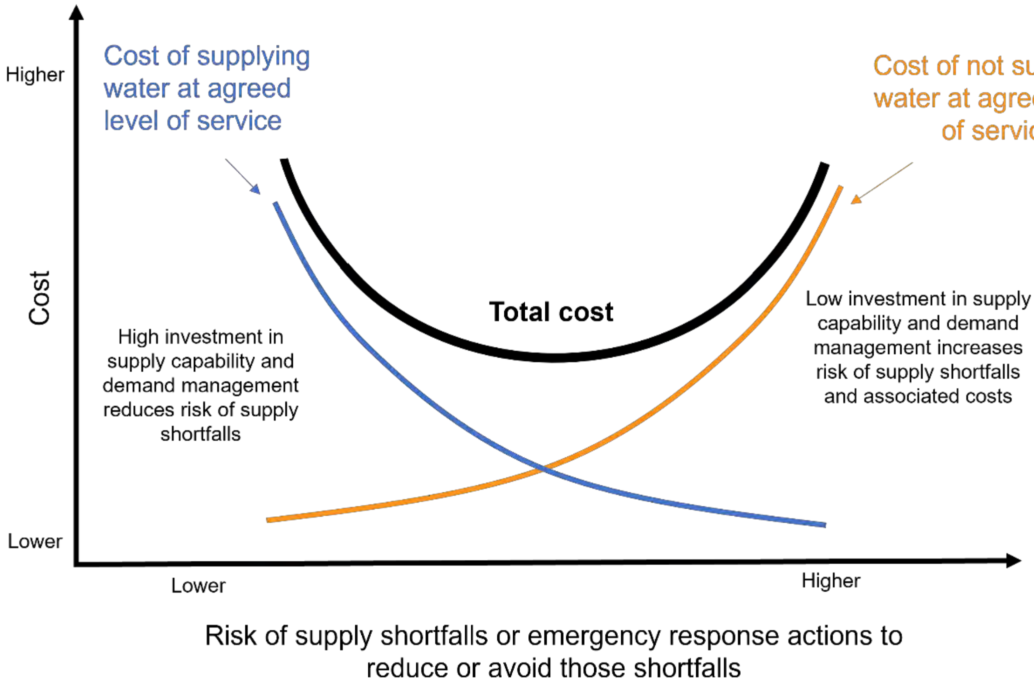


Figure 5 Trade-off for setting level of service objectives

The cost to the community of not providing a given level of service can range from loss of aesthetics (e.g. fountains being turned off), to loss of amenity (e.g. sports grounds unable to be used), loss of assets (e.g. lawns), and loss of income (e.g. reduction in visitors affecting the tourism industry or impacts on product sales and services for the gardening industry). It can also result in price bill shock (e.g. water service providers passing on costs to generate more manufactured water, to pump water over longer distances from less accessible water sources, to purchase water allocations from other users, to drill and treat supply from emergency groundwater bores, or by paying inflated prices for rushed capital investments in new supply infrastructure, etc.). Ultimately, poor planning can lead to loss of community, with people and businesses moving to where they can source a more reliable water supply.

Case study: Day Zero forecasts for Cape Town, South Africa

Prolonged, severe restrictions, which create anxiety for a community that it may run out of water, are untenable and must be avoided. Lessons from overseas highlight the severe and broad-ranging social and economic consequences of not being able to maintain adequate water supplies for basic water needs. An example is the City of Cape Town’s estimate of “Day Zero” during drought in 2017 and 2018, when a specific date was nominated for when the city would run out of water. See Ziervogel (2019) for a description of water resources planning activities in the City of Cape Town leading up to and during that drought event.

A balance exists where there is an acceptable level of risk for customers. This trades off the cost to supply water (through investment in supply and demand management measures) with the cost of not supplying water (through water restrictions, or the use of higher cost emergency supply measures, at an acceptable frequency and/or duration). Some communities may have to pay more than others to achieve the same level of service and some communities may be willing to pay more to achieve a higher level of service. The costs of not supplying water will also vary from one supply system to the next.

There are also different sectors of the community, each with different interests and a different willingness and ability to pay for water. However, it is only through engagement with customers that an acceptable level of service for the majority of those customers can be identified. Strategies can then also be developed to offset potential impacts on individual customers or customer groups who may be more adversely affected at that level of service.

2.4 Stakeholders and their roles

Water service providers, government regulators, government asset managers, and the community all have an important role to play in urban water resources planning. It is the role of a water service provider to broker an agreed planning strategy with its customers, subject to regulatory requirements and constraints, and with the support of other government agencies and the broader community.

The objectives for urban water resources planning differ for water service providers and government regulators. A water service provider's focus is primarily local, creating solutions that are tailored to the specific needs, challenges, and opportunities of their supply systems. The role of government regulators is often to oversee many water service providers, creating the conditions to enable and promote good practice urban water planning, and monitoring outcomes that can be aggregated across many water supply systems. Government is also responsible for regulating the use of all water resources, including the provision of water for the environment, and for investing public funds more broadly to create and maintain healthy communities and a vibrant economy. As a result, the performance metrics of interest to water service providers and government can be different.

2.5 Challenges and opportunities

Prior to commencing urban water resources planning, water service providers have an opportunity to influence the strategic environment in which that planning occurs (WSAA, 2014). This includes engaging with government regulators and contributing to public debate about the role of water service providers across its full range of services, and raising awareness of those services. This recognises that water service providers hold unique knowledge and skills that are important to broader community planning.

Urban water resources planning can be complex, requiring a range of tools, skills, and viewpoints. Urban water resources planning requires both technical assessment and social engagement. Urban water resource planning is therefore a team exercise. Planning outcomes are improved by collaboration between engineers, scientists, operators, finance managers, and communications staff within a water service provider, as well as with the customer base. Ongoing engagement with customers, colleagues, and stakeholders improves the level of knowledge about urban water resources planning, allowing those groups to participate in the planning process more effectively.

Urban water resources planning takes place in an environment where many inputs are subject to significant uncertainty, as outlined further in Section 2.6. The main uncertainties typically include climate variability, climate change, and population growth uncertainty, but can also include regulatory uncertainty associated with changes in environmental, cultural, or social values over time. Whilst these uncertainties represent a significant challenge for decision making, they also present an opportunity to explore and understand supply system behaviour more comprehensively, and to engage with stakeholders more meaningfully about what they want from their supply system. Various planning approaches are available to enable well-considered decision making despite this uncertainty, as outlined further in Sections 3 to 7.

Most of our urban supply systems were developed a long time ago, based on the knowledge, regulatory conditions, and community expectations at the time. Urban water resources planning and the socio-economic environment in which it operates have significantly evolved over time. This presents opportunities for urban water resource planners to develop solutions that use water more efficiently across a supply system. It also creates the potential to utilise a broad range of drinking and non-drinking water resources that may not have been fully considered in the past. In some locations, this may involve adjusting the mix of water resources and how they are used to achieve better outcomes for the environment, Traditional Owners / Mana whenua[2], industry, and the broader community. Urban water resources planning is not a set-and-forget activity. Given the various challenges and opportunities that can emerge over time, there is a need for ongoing monitoring of the supply system, and tracking of the water resource plan implementation actions. Plan implementation also involves reflection on lessons learned, adaptation in response to changing water resource conditions, community expectations, and government policy positions, and periodic update of the plan. This is illustrated in Figure 6.

Table 5 Water resource planning principles for timing and nature of planning activities

Title	Principle
RP-4: Ongoing effort	Urban water resources planning is a cyclic, ongoing activity consisting of plan development, implementation, monitoring, adaptation, reflection, and renewal.

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[2] Traditional owners in Australia, Mana whenua in New Zealand

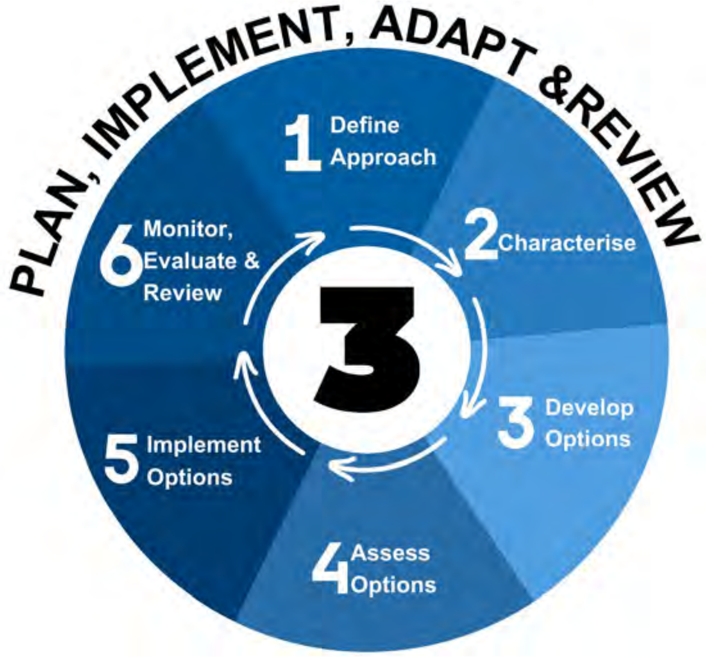

Figure 6 The cyclic nature of urban water resources planning (WSAA, 2014)

The timeframe for a planning cycle will depend upon the current and projected performance of the supply system, and the rate of change of the influences on that performance. A four-to-five-year planning cycle is typically adopted, with earlier renewal of a plan if required.

Prompts for earlier renewal could include significant new knowledge becoming available, such as unplanned changes in supply system influences that fall outside of the water resource plan assumptions. It could also include the emergence of factors that compromise the water service provider’s ability to implement its planned course of action (e.g. changes in regulation that impose new limits on access to water). Annual review of the water resources plan, if only brief, will help to formally capture any such changes, and ensure that the water resources plan remains valid prior to the next renewal of the plan.

2.6 Sources of uncertainty

Some uncertainty permeates most aspects of urban water resources planning. This contrasts with expectations for decision-making, where planning activities are expected to lead to a definitive plan of action, regardless of any input uncertainty. The sources of uncertainty for urban water resources planning are many and varied, and with different degrees of uncertainty. These include, but are not limited to:

- Climate variability, including variability beyond that known from historical instrumental records;
- Projected climate change uncertainty from global climate model uncertainty, emissions scenario uncertainty, and global climate model downscaling uncertainty;
- Uncertainty in water resource response to climate variability and climate change, such as that due to scientific and water resource model uncertainty about local hydrology and hydrogeology;

- Population growth uncertainty, primarily due to uncertainty about future net migration between cities and rural areas, between States, and between countries, as well as assumptions around birth and death rates, and employment opportunities;
- Per capita or per connection water use uncertainty. This can be due to changes in demographics, dwelling type, water use behaviour, and the availability and development of non-drinking water sources for fit-for-purpose uses;
- Major commercial and industrial water use uncertainty, which can be influenced by business viability, global commodity prices, consumer demand, etc;
- Changes in community aspirations over time. This could include wanting to provide more water for the environment or cultural uses, or placing greater value on creating liveable green and blue spaces. It could also involve a desire for greater flood protection from urban water resource infrastructure in the context of higher rainfall intensity projected under climate change. It may also also include changes in risk appetite and willingness to pay for a given level of service, particularly during and after the effects of drought;
- Regulatory uncertainty, including in response to changes in community aspirations, such as potential changes in water requirements for environmental purposes and Traditional Owner / Mana whenua purposes; and
- Political uncertainty, where the policy settings for a water service provider may change with changes in government, impacting on service provider resourcing and strategic direction.

At first glance this long list of uncertainties can be overwhelming. However there are strategies available to work through these uncertainties to develop urban water resource plans that provide confidence for water service providers and their customers. The following specialist topic areas explore some of those strategies and the principles that underpin them.

3. SPECIALIST TOPIC AREAS

Urban water resources planning involves drawing upon a diverse range of knowledge and skills, some of which are highly specialised. The following sections of the Framework discuss these specialist topic areas, with more extensive discussion for topic areas that involve contested ideas, or newly developed approaches. Knowledge in these topic areas is continuing to evolve – the following should therefore be regarded as a starting point for developing your own thoughts, and for engaging with other water industry practitioners and researchers.

The format for presenting information on these specialist topic areas is:

i. What is the topic area?
ii. Why is it relevant to urban water resources planning?
iii. Planning principles relevant to the topic area.
iv. A discussion of the planning principle and references to supporting information.
v. Future research and investigation for the topic area, where relevant.

These specialist topic areas are presented under four themes: understanding your current supply system, understanding your water supply needs, future demand and water availability, and decision making. Within these themes, topics are presented in no particular order.

4. UNDERSTANDING YOUR CURRENT SUPPLY SYSTEM

4.1 Current water use

What is it? An understanding of the current demand for water from your supply system from different user types, including non-revenue water.

Why is it relevant to urban water resources planning? A current demand estimate allows current supply system performance to be assessed and provides a starting point from which demand projections can be made. Relevant principles are listed in Table 6 and discussed below.

Table 6 Water resource planning principles for current water use

Title	Principle
CU-1: Quality assurance	Checking your bulk metered bulk water demand data for anomalies and monitoring it for trends, to identify metering errors quickly, will maximise the data available for use in planning.
CU-2: Estimating current bulk water use	Estimates of current bulk water use should take into account input uncertainties and trends, especially climate variability, treatment and delivery system losses, the impact of restrictions, and any significant changes in the number of connections over time.
CU-3: Demand components	Dividing current water use into its various components (drinking vs non-drinking water uses, residential vs commercial vs industrial uses, non-revenue water, supply by agreement rural use) and tracking these over time will help to provide insights into the variability and trends in total water use.
CU-4: Total, restrictable, and unrestrictable demand	For supply systems with a restriction policy, expressing demand reductions under restrictions as a percentage of the restrictable demand makes it easier to compare demand response throughout the year and across supply systems.

Discussion of principles:

Quality assurance: The quality of water supply system modelling and the water resource planning decisions that it informs, is dependent on the quality of input information. Most climate and streamflow related datasets are quality assured by meteorological agencies and hydrographic data collectors according to industry standards and guidelines (e.g. BoM, 2019), including quality codes that classify the quality of the data. Bulk water meters operated by water service providers have historically not been subject to the same level of quality assurance, sometimes resulting in extended periods of data not being available for use in water resource modelling and planning. By setting up quality assurance procedures to check for anomalies and trends in the demand data that is being collected, it is more likely that better quality data will be collected more often. This maximises its value for water resource planning.

Estimating current bulk water use: Water use will fluctuate or change over time, particularly due to climate variability. It can also be influenced by changes in treatment and delivery system losses, water use restrictions, and any significant changes in the number of connections over time.

Demand models fitted to recent historical data can be used to estimate current bulk water use. Various urban demand modelling approaches are available. These can include statistical models (Weber, 1989; Beatty, 2009), end-use models (e.g. Thyer et al., 2011), agent-based models (e.g. Koutiva and Makropoulos, 2016; Sattler et al., 2023), econometric models, and more recently machine learning models or hybrid statistical and machine learning approaches (e.g. Zubaidi, 2023).

Statistical models typically involve statistical regressions between metered demand and climate variables, on a monthly or daily time step. These regressions can also include other variables such as the number of connections, population, demographic information, day of the week, or holiday periods. Statistical models are well suited to understanding total bulk water demand for a supply system.

End use models or agent-based models can inform demand management strategies that target improved water use efficiency and drinking water demand substitution. End-use models involve estimating water use from different types of activities (e.g. for toilet flushing with a single versus dual flush toilet) and then assigning a portion of households with each type of activity (e.g. half of households have a single flush toilet, and half of households currently have a dual flush toilet). End use models can be used to forecast changes in the market penetration of more water efficient fixtures and appliances over time.

Agent-based models, although less commonly implemented to date, operate on a similar principle, but are based on individual water user behaviour rather than household behaviour. In contrast, econometric models group households by type (e.g. owner occupier vs tenant, and by property size) and assign water use characteristics to each household type.

Key to these types of end-use and agent-based models is the quality of information used to assign usage volumes and distribute water use behaviours amongst users. Any demand models should be able to demonstrate the suitability of their input assumptions, and the quality of the demand model fit to recent historical data.

In an emerging area of science, machine learning models have recently been used to estimate urban demand at various scales, with these models performing better when combined with statistical modelling (Zubaidi, 2023). Wellington Water's urban demand was recently estimated by NIWA using this kind of hybrid approach. It used the outputs from a trained statistical model as an input to the machine learning model, which enhanced the model's pattern recognition capabilities. The methods and outcomes of this work completed for Wellington Water are currently being drafted.

Demand components: Dividing current water use into its various components (drinking vs non-drinking water uses, residential vs commercial vs industrial uses, non-revenue water, supply by agreement rural use) and tracking these over time will help to provide insights into the variability and trends in total water use. It also allows each of these demand components to be separately projected when estimating future water use. This ensures that actions to reduce demand or substitute its water source can target where those actions will be most effective.

Total, restrictable, and unrestrictable demand: If the supply system has been subject to recent periods of water restriction, then either those periods can be excluded from estimates of current (unrestricted) demand or an explicit allowance can be made for those demand reductions. Such an allowance can be based on observations of reduction in demand due to restrictions (e.g. Neal et al., 2010) or based on a theoretical assessment informed by demand responses in similar communities, or informed by an end-use demand model.

Estimated demand reductions due to restrictions can be expressed as a percentage reduction in total demand, or a percentage reduction in restrictable demand. Restrictable demand is that component of demand that can be subject to water restrictions, and typically includes outdoor water use from the drinking water supply system. Unrestrictable demand typically includes water for commercial and industrial purposes, and for in-house use, noting that these can still be restricted in emergency situations. For supply systems with a restriction policy, expressing demand reductions under restrictions as a percentage of the restrictable demand promotes the comparability of demand response throughout the year and across supply systems. Where demand reductions are expressed as a reduction in total demand, the seasonal variance in that demand reduction can be masked. For example, restrictions that generate a 10% reduction in annual demand are likely to result in a more than 10% reduction in drier months (when the outdoor water use would ordinarily be higher) and potentially no reduction in wetter months. Similarly, for equivalent restrictions in two nearby towns, but with vastly different proportions of non-restrictable industrial and commercial water use, those restrictions will not generate the same percentage reduction in total demand. By expressing demand reductions as a percentage of restrictable demand, the demand response is more likely to be similar, because it has been made non-dimensional with respect to the volume of restrictable demand. It is recognised that the percentage reduction in restrictable demand will vary from one supply system to the next (e.g. with different household garden sizes, different levels of compliance with regulations, etc.), but by removing the unrestrictable component of demand from the assessment of demand reduction, any estimate of that reduction is likely to be more robust across supply systems.

Future research and investigations:

Table 7 Future research and investigation to support ongoing improvement and understanding of current water use

Research and investigation area R1: Smart meters: Continued rollout of smart meters.
Research and investigation area R2: Uniform water restrictions: The development of uniform water restrictions in homogenous climate regions within State boundaries across Australia and New Zealand.

Smart meters: Continued support for the rollout of smart meters to help water service providers better understand customer water use behaviour at finer temporal and spatial scales. An example of this is Perth's Smart Water Meter Pilot (Water Corporation of Western Australia, 2023b). Smart meters better support end use demand models that inform demand management strategies, including fit-for-purpose demand substitution with supply from non-drinking water sources.

Uniform water restrictions: A uniform 4-stage water restriction policy has been implemented in Victoria (DEECA, 2023). If a customer knows what water use behaviours are permissible under a given stage of restriction in one part of the State, when that user moves to another part of the State, either temporarily or permanently (e.g. if living in one supply system area and working in another), then those same water use expectations will apply for a given local level of restriction. The availability of a uniform water restriction policy also reduces workload for local water service providers, because they do not have to derive their own local policy. They also do not need to defend it relative to different policies in nearby supply systems. The level of water restriction implemented at any given location can still vary, as this will be a function of local supply system conditions.

It is recommended that uniform water restrictions be developed in homogenous climate regions within State boundaries across Australia and New Zealand. This may need to be supported by a characterisation of climate conditions and the identification of homogenous climate regions, both now and into the future. It may also require an understanding of the origin and applicability of different water restrictions that are unique to any given supply system.

4.2 Supply system operation

What is it? The supply system infrastructure, legal entitlements to water, and operating rules.

Why is it relevant to urban water resources planning? Understanding supply system operation, and representing it with water resource models, is a pre-cursor for understanding supply system performance. Relevant principles are listed in Table 8 and discussed below.

Table 8 Water resource planning principle for supply system operation

Title	Principle
SO-1: Non-modelled rules	Not all operating rules can be modelled, but they should all be documented, with any differences between the two acknowledged to support well-informed decision-making.
SO-2: Water resource model quality	The quality of the performance metrics used to inform water resource planning will be influenced by the quality of the water resource model used to generate them.

Discussion of principles:

Non-modelled rules: Not all operating rules can be represented by water resource models. For example, operating rules to maintain a certain water quality in a storage cannot be directly represented by a water resource model that does not also include water quality parameters. At best they can only be indirectly represented using surrogate water quantity variables. Differences can also occur between theoretical operation and actual operation, with deviations from theoretical operation sometimes occurring due to constraints on water movement, particularly for asset management purposes, that can impact supply system performance. Acknowledging differences between actual and modelled operating rules will help decision makers understand what aspects of the supply system operation are not being modelled, so that this can be factored into subsequent decision making.

Water resource model quality: Water resource models are subject to data input uncertainties, as well as any uncertainties in representing operating rules and water resource infrastructure capacities. As such they are a simplified representation of the actual supply system. The better those models can be verified against recent historical behaviour, the more reliable they will be for informing water resources planning. In the interests of transparency in decision making, decision makers should be informed of any systemic bias in a water resource model that could affect estimates of supply system performance. Further discussion of water resource modelling considerations is presented in Section 4.7.

4.3 Current water availability and non-stationarity

What is it? Current water availability is an estimate of how much water a supply system has access to, both (i) right now in real-time and (ii) at an assumed level of service under current supply system operation, taking into account input uncertainties. Non-stationarity refers to any dataset that contains trends over time.

Why is it relevant to urban water resources planning? Current water availability informs the ability of the supply system to currently meet performance objectives. Historically, urban water resources planning assumed stationary hydro-climate and demand conditions. For many supply systems, this will not necessarily be the case. Relevant principles are listed in Table 9 and discussed below.

Table 9 Water resource planning principles for current water availability and non-stationarity

Title	Principle
NS-1: Non-stationarity	Water resource supply system inputs are often not stationary, which affects how useful historical information is for estimating current water availability. Non-stationarity can require the use of approaches to limit input data or to de-trend or adjust that data prior to its use.
NS-2: Systems with large storage capacity	For supply systems with large storage capacity relative to demands and inflows, and non-stationary inputs, performance metrics may be more accurate when assessed across replicates or scenarios rather than over time.

Discussion of principles:

Non-stationarity: Various statistical tools are available to identify non-stationarity in historical datasets. These include tests for identifying step changes and gradual changes in data, or deviations from a reference stationary dataset. Tests that assess the statistical significance of any non-stationarity will be more rigorous and defensible than those that do not, with examples of statistical tests in Amirthanathan et al. (2023).

Historical input data that is not stationary can affect our estimates of current water availability and therefore supply system performance. A practical example of this was the supply system yield for Perth's water supply system, prior to the diversification of its water sources. Inflows to Perth's reservoirs in the decades from the mid-1970s onwards exhibited successive large reductions (Smith and Power, 2014). Utilising raw inflow data prior to the mid-1970s would artificially inflate estimates of current water availability, because the climate conditions have changed and Perth's water supply catchments now receive much less rainfall. Similar observed changes in historical streamflow have now been identified at many locations throughout Australia, mostly in the late-1970s and the 1990s (Amirthanathan et al., 2023).

The better that a practitioner can understand the reasons for non-stationarity in a dataset, the more likely that it can be de-trended and retained for use (e.g. as outlined in DELWP, 2020), rather than truncated and discarded. Common reasons for non-stationarity include climate change, population growth, intercepting activities, past bushfires, changes in upstream water use or bore interference, changes in soil moisture storage, etc. They may also be due to changes in instrumentation, or measurement error. Changes in rainfall-runoff response over time in a drying climate are discussed further in Section 6.5. Climate independent water sources (see Section 4.4), such as supply from desalination, are generally stationary.

Systems with large storage capacity:

As discussed further in Section 5.1, reliability of supply is typically estimated in two different ways:

i. Over time (e.g. an X% likelihood, or as a likelihood of Y years in 10, or Z years in 100) from a single climate sequence; or
ii. Across replicates or scenarios at a given point in time (e.g. an X% likelihood in year 2030, a Y% likelihood in the year 2040, etc.).

In supply systems where storage capacity is small relative to demands and inflows, supply system performance is governed by input conditions now, with relatively little influence from past input conditions. However, when storage capacity is large relative to demands and inflows, current water availability is governed not only by the input conditions right now, but also the input conditions over previous months and years. Where those inputs are dynamically changing over time, such as due to population growth or climate change, it can be argued that performance can no longer be assessed using stationary inputs over time (i.e. method (i) above), as has been done traditionally in long-term reliability of supply or yield assessments. This is because these systems effectively never reach a steady state. For these kinds of supply systems, reliability of supply can be assessed using method (ii) above. This utilises modelled information from the current resource position, projected forward using a stochastic or multi-replicate representation of non-stationary inputs over time. Such an approach better accounts for changing input conditions over time due to longer term trends.

4.4 Climate independent water sources

What is it? Climate independent water sources are those whose availability does not vary appreciably with climate. It can include water sourced from desalination plants and recycled water treatment plants. It is acknowledged that recycled water availability can sometimes vary with climate, albeit to a much lesser degree than climate dependent water sources, such as water sourced from rivers. This includes increased water availability within the sewer network from stormwater infiltration during wet periods, and reduced water availability due to in-house water use behaviour change during droughts.

Climate independent water stored in uncovered surface water reservoirs after its production will be subject to evaporative losses. These losses are climate dependent and will vary seasonally, from year-to-year, and with projected climate change.

Groundwater recharge from rainfall is climate dependent. However, water stored in confined aquifers or deep unconfined aquifers can be considered a climate independent water source for a finite period of time. This will be the case particularly where there are very long lag times (of years, decades, or more) between groundwater recharge events and the groundwater level or pressure response at the depth of extraction. Artificial recharge of groundwater from a climate independent water source can be used to improve both the climate resilience and sustainability of groundwater supply, as well as being consistent with the principles of a circular economy (Jazbec et al., 2020) that reduces waste.

Case study: Improving the climate resilience of Perth's groundwater supply

Perth's groundwater replenishment scheme provides recycled water of drinking water quality to a local aquifer, for subsequent re-treatment and reuse for drinking water when it is needed in subsequent years. This scheme was developed after a several year trial, including review and ongoing regulation by the Environmental Protection Authority. It has been in operation since 2017 and expanded in 2022 (Water Corporation of Western Australia, 2023a). The scheme balances groundwater extraction with replenishment to ensure that the groundwater extraction is sustainable and much more climate resilient, because it is replenished from a climate independent water source.

Why is it relevant to urban water resources planning? Access to climate independent water sources reduces or eliminates a major source of uncertainty for urban water resources planning, namely the uncertainty in water availability due to climate variability. Climate independent water sources can be a source of enduring supply during drought. These water sources are often higher cost to create and operate. However, being able to provide a higher proportion of critical human water needs from climate independent water sources provides a higher level of certainty to communities during drought.

Relevant principles are listed in Table 10 and discussed below.

Table 10 Water resource planning principles for climate independent water sources

Title	Principle
CI-1: Enduring supply	Climate independent water sources can be a source of enduring supply during drought.
CI-2: Non-drought supply risks	Climate independent supplies are resilient to drought but are not immune to all other risks. Water resource planning should not assume that climate independent supplies are resilient to all risks.
CI-3: Artificial recharge builds resilience	Artificial recharge of groundwater from a climate independent water source can be used to improve both the climate resilience and sustainability of groundwater supply.
CI-4: Redress opportunities	Climate independent water sources can be used to address historical overuse of surface water or groundwater through supply substitution, to improve environmental, cultural, and community outcomes.

Discussion of principles: Planning for climate independent water sources is similar in nature to planning for any water source, other than recognising the higher water security value of climate independent water sources. Identifying a preferred supply portfolio including climate independent water sources is a decision-making process that considers supply system performance and its robustness, as outlined for all water sources (see Section 7.3).

Enduring supply: Climate independent water sources can be a source of enduring supply during drought. This means that supply can remain continuous throughout a drought, because the drought has little or no effect on the reliability of supply from a fully climate independent water source. Where a water source is largely but not completely climate dependent, such as for purified recycled water, the assumed volume that could be considered as an enduring supply might be lower than what is typically available. Alternatively, in some supply systems, the reliability of supply from purified recycled water might diminish to the extent that it would no longer be an enduring supply. Purified recycled water will most likely be an enduring supply where it is coupled with a genuinely climate independent source of water for customers, such as a seawater desalination plant, that results in a continuous supply of wastewater for recycling.

Climate independent water sources are often a higher cost source of water, in which case their operation can be limited to times when other lower cost supply sources are in short supply. This higher cost can include higher greenhouse gas emissions, if the energy sources for water production are not renewable or fully offset. This approach of intermittent operation utilises climate independent water sources as a drought or emergency response measure. For some water service providers, it is more cost effective to operate their climate independent water sources as a baseload supply all of the time (e.g. as currently occurs in Perth). This can particularly be the case for desalination plants. Some water service providers have found it to be more cost effective to run these plants continuously (but not necessarily at full capacity) to maintain the plant in good working order, thereby saving on other maintenance and replacement costs over the design life of the plant.

Non-drought supply risks: Just because a climate independent water source is immune to drought, does not mean that it is immune to all other risks. Other risks can include infrastructure damage, and competition from other water users (e.g. deep groundwater bore interference or saline intrusion). A historical example of this was the Sydney Desalination Plant, which was offline from 2016-2018 for repairs after a tornado tore the roof off the plant (Sydney Desalination Plant, 2017). Fortunately, this occurred at a time when water from the desalination plant was not needed. This example highlights the need to consider the possibility of supply system shocks (see Section 7.5), even for climate independent water sources. Stress testing of a supply system without access to some of its climate independent supplies can help to understand the risks associated with these kinds of shocks.

Similar to other water sources, climate independent water sources can be subject to supply constraints. These constraints can include lead times for operation if the climate independent water source is not always in operation (e.g. re-starting desalination plants can sometimes take several months), any regulatory conditions placed on those water sources, and the proportion of the supply system that the climate independent water source can reach (e.g. recycled water that can only physically supply new residential and industrial customers where a third pipe has been installed, but not existing customers in older areas). It can also include water quality constraints associated with treatment processes for different or for blended water sources, and customer taste considerations when alternating supply from different sources.

Artificial recharge builds resilience: This principle was illustrated by the case study of Perth's groundwater supply, described above.

Redress opportunities: In some regions, water from climate dependent water sources has been over-allocated, creating stress for ecosystems and reducing the cultural value of water sources. Climate independent water sources can be used to address historical overuse of surface water or groundwater through supply substitution, to improve environmental, cultural, and community outcomes.

Such an approach is discussed in DELWP (2022), where manufactured water was regarded as an opportunity to free up river water for other uses, such as returning water to Traditional Owners / Mana whenua and the environment. In considering such an approach, the additional cost of water production (including the maintenance benefit of keeping some climate independent water sources in continuous operation) needs to be less than the value of returning water to rivers and aquifers.

4.5 Fit for purpose water use

What is it? Water that is fit for purpose can be provided at a suitable quality for its intended use. Higher quality water is required for drinking water purposes. However lower quality water can still be fit for purpose for other applications, such as for some agricultural uses, industrial uses, for watering parks and gardens, and for some in-house uses (e.g. toilet flushing). Lower quality water sources include untreated rainwater, stormwater, and recycled water that is not treated to a drinking water standard. When recycled water is regarded as an asset and appropriately treated, it can potentially also be used for a variety of other community purposes, such as for environmental water delivery to wetlands, aquifers, and rivers.

Why is it relevant to urban water resources planning? Urban water resources planning has traditionally focussed on drinking water supply. A more holistic approach to water planning recognises the opportunities to substitute drinking water sources with non-drinking water sources for applications where drinking water quality is not required. This frees up drinking water sources for their highest value use as drinking water. Relevant principles are listed in Table 11 and discussed below.

Table 11 Water resource planning principles for fit-for-purpose water use

Title	Principle
FP-1: Scale of fit-for-purpose water use	Water that is not treated to a drinking water standard can be fit-for-purpose at a variety of spatial scales, from households to neighbourhoods to whole of system scales.
FP-2: Fit-for-purpose design standards	The design standard for a non-drinking water supply system need not necessarily be as high as that for a drinking water supply system.
FP-3: Users switching supply sources	Where users have a choice of different quality water sources, there is no guarantee that drinking water will exclusively be used for drinking water purposes. Demand assumptions need to consider the potential for users to switch supply sources, particularly during extended drought.
FP-4: Collaboration to provide clarity	Fit-for-purpose water use needs to be underpinned by a regulatory framework, a decision-making framework, community engagement, clear ownership, and multi-agency collaboration.
FP-5: Purified recycled water for drinking	The use of purified recycled water for drinking water purposes should always be an option for discussion with communities on water supply enhancement options.

Discussion of principles:

Scale of fit-for-purpose water use: Traditionally, urban water planning has focussed on finding water sources that contribute to the whole or a substantial part of a supply system. One of the features of fit-for-purpose water sources is that they can be employed at different scales, but still contribute (on aggregate) to reducing demand on the potable water system. At a household scale, this can include plumbing rainwater tanks for toilet flushing and for use in garden watering. At a neighbourhood scale, it can include utilising recycled water from local wastewater treatment plants or stormwater harvesting schemes. Large scale systems can also be implemented using third pipe networks, or as part of water source substitution for agricultural water users or the environment, particularly where they share the same raw water source as an urban water service provider.

Fit-for-purpose design standards: For non-drinking water supplies, the design standard for the supply system does not need to be as high as that for the drinking water supply system, provided that a lower design standard does not compromise safety or create additional environmental risks. The design standard should align with end user expectations for the reliability of the non-drinking water source. For example, not having access to recycled water for garden watering will have less impact on customers than not having access to a drinking water supply for the same duration. A higher design standard may result in significant additional costs associated with additional water storage and treatment. Water demand for a given application (e.g. garden watering) may also potentially vary depending on the source of water, due to perceptions about its scarcity value and (if applicable) water supply price differences.

Users switching supply sources: Where users have a choice of different quality water sources, there is no guarantee that drinking water will exclusively be used for drinking water purposes. Demand assumptions need to consider the potential for users to switch supply sources, particularly during extended drought. Lot scale or neighbourhood scale integrated water supply monitoring and modelling can inform the likely additional volume per household of non-drinking water demand to expect on the drinking water supply system under different climate conditions.

Collaboration to provide clarity: Fit for purpose water use needs to be underpinned by a regulatory framework, a decision-making framework, community engagement, clear ownership, and multi-agency collaboration. This is discussed in further detail in Skinner and Satur (2020). Planning fit for purpose water use requires an understanding of the availability and quality of different water sources, and the regulations that govern their permissible uses in your jurisdiction. It also requires an appreciation of the spatial and temporal distribution of non-drinking water demands relative to non-drinking water sources.

Planning can be supported by a decision-making framework that takes into account a broad suite of performance metrics. These recognise broader community and whole-of-life cycle costs and benefits that can often be associated with fit-for-purpose water use. This can include, for example, recognising the benefits of maintaining green and blue space during droughts, or cost avoidance for wastewater discharge infrastructure and impacts.

Community engagement is required to establish the desire to utilise non-drinking water sources. It can also be used to educate end users on an ongoing basis about the different quality of their water sources, and the (in)appropriate uses of those water sources.

Purified recycled water for drinking: For recycled water, reuse for urban water supply can either be indirect or direct. Indirect reuse for drinking water involves supplying purified recycled water to a location upstream of water supply treatment facilities, often remote from those facilities. Any recycled water is then diluted and re-treated prior to its supply into the drinking water supply system. Direct reuse for drinking water supply involves supplying purified recycled water directly into the drinking water supply system without further re-treatment. To date communities in Australia and New Zealand have not allowed direct reuse for drinking water, and in some cases also rejected indirect reuse. In practice, indirect reuse occurs along many major rivers, with treated wastewater from towns discharged into rivers, where it is diluted, diverted and re-treated by other towns for drinking water supply further downstream. This also occurs in the ocean where treatment plants discharge treated wastewater that is diluted in the ocean, and potentially then retreated further along the coastline by a desalination plant.

Locations around the world where schemes to supply purified recycled water for drinking have been developed are mapped in Figure 7. This includes Perth's groundwater replenishment scheme (Water Corporation of Western Australia, 2023a) and south-east Queensland's Western Corridor Scheme (Seqwater, undated). WSAA supports engagement with communities about all water supply options being on the table as previously outlined in WSAA (2020). Purified recycled water can then be fairly assessed against other options, to identify whether or not it is part of the preferred solution to maintain performance objectives into the future. Engagement on the use of recycled water for drinking water purposes should be sensitive to different cultural views on this topic for different community groups, and be guided by government policy in your jurisdiction about public engagement on this issue.

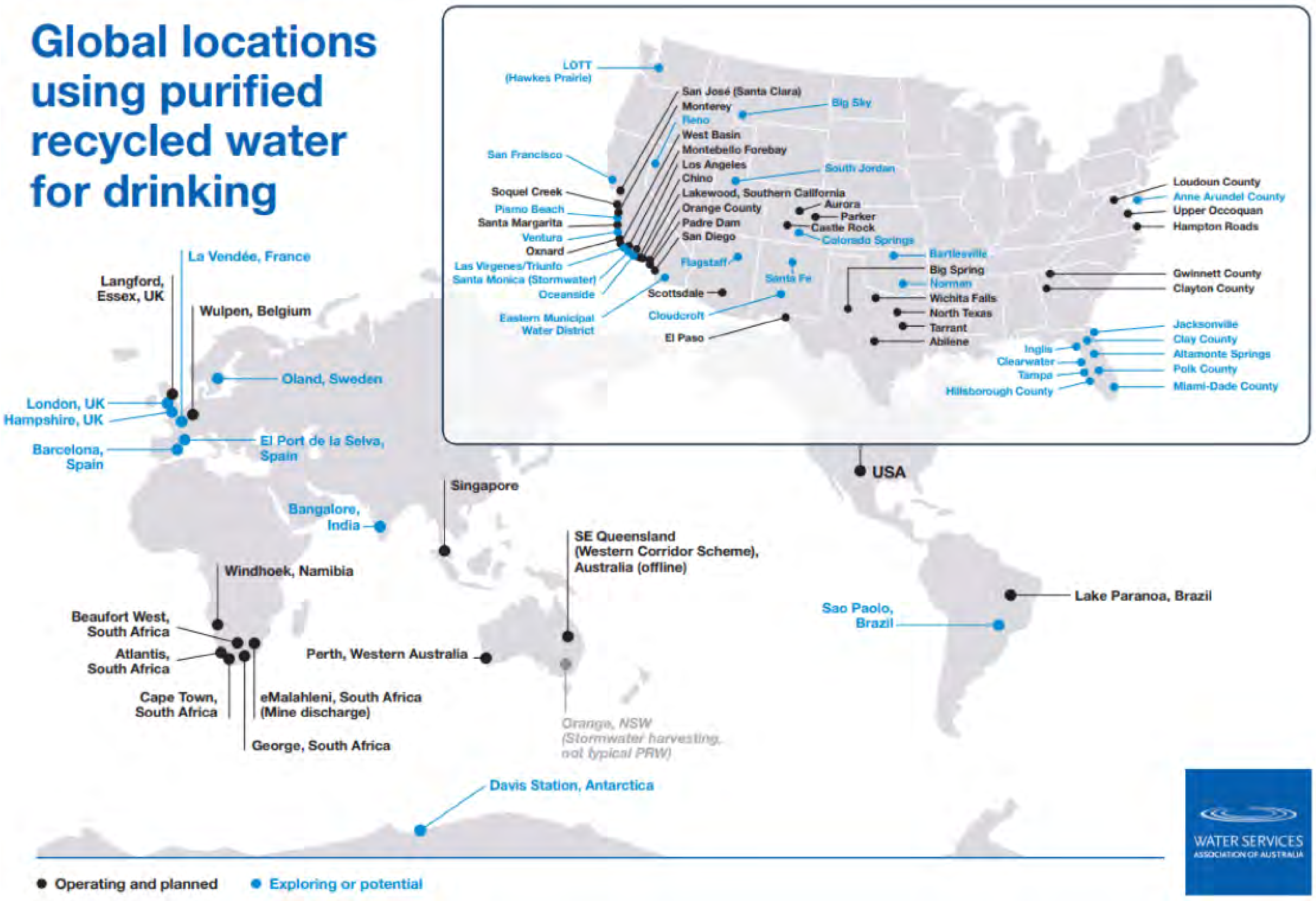

Figure 7 Places with formal purified recycled water for drinking schemes (WSAA, 2022)

4.6 Climate variability

What is it? Climate variability is the fluctuation in weather from day to day, for different seasons, for different years, and for different multi-decadal periods. Climate indicators linked to climate variability associated with droughts and floods in parts of Australia and/or New Zealand include the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the Southern Annular Mode (SAM), the Madden-Julian Oscillation (MJO), and the Inter-decadal Pacific Oscillation (IPO), amongst others (BoM, 2023). Climate variability is a separate consideration to climate change, however climate change may have an impact on climate variability (refer Section 6.2).

Why is it relevant to urban water resources planning? Climate conditions across Australia and New Zealand can be highly variable. Rainfall variability determines the reliability of runoff and recharge in wet versus dry periods. For supply systems supplied predominantly from climate dependent water sources, climate variability can be a key factor in estimating water availability from those sources. It can also be important for determining storage requirements to maintain adequate supply during drier periods. Variability in air temperature, evaporation, and evapotranspiration also influence variability in the demand for water and supply system losses. Relevant principles are listed in Table 12 and discussed below.

Table 12 Water resource planning principles for climate variability

Title	Principle
CV-1: Level of effort to understand climate variability	Where climate variability is likely to heavily influence performance metrics and therefore planning outcomes, a higher level of effort is warranted to better understand climate variability.
CV-2: Length of climate record to adopt	The longer the available instrumental climate record, the better that climate variability can be characterised.
CV-3: The possibility of more severe droughts	Historical climate variability, as observed in the instrumental climate record, provides only a sample of possible climate variability. Future droughts (and floods) more severe than those observed in the instrumental climate record are entirely plausible.
CV-4: Suitability of paleoclimate information	The suitability of paleoclimate proxy records to represent local climate conditions varies considerably. The quality of those records, including their correlation with local climate conditions, should be critically reviewed prior to their adoption. Paleoclimate proxy records may not be suitable for use in some locations.
CV-5: Value of climate independent water sources	Regardless of the approach to assessing climate variability, the greater the climate variability of local supply sources, the greater the value that climate independent water sources can be.

Discussion of principles:

Level of effort to understand climate variability: There are many ways of characterising climate variability, each requiring a different level of effort with different types of insights generated. Initial steps include identifying which climate and water availability indicators are of most relevance to the supply system, how they have varied historically, and any knowledge (observed or modelled) of supply system performance under that historical climate variability. Based on this information, the potential vulnerability of the supply system to climate variability can be broadly classified (i.e. the broad likelihood that climate variability will affect supply system performance and to what extent), as well as the consequences of poor system performance if planning decisions are made on the basis of inaccurate information about climate variability.

Actions to improve the characterisation of climate variability include manipulating the instrumental record to create long term current climate series, using climate dependent models (e.g. demand models, rainfall-runoff models, groundwater models), paleoclimate reconstructions, and/or stochastic data generation. Other techniques such as empirical mode decomposition have also been used to identify underlying climate cycles within historical climate data, but for most applications, an understanding of the links between known climate influences (e.g. ENSO, IOD, IPO, etc.) will generate a more practical understanding of underlying climate cycles of relevance to your water supply system.

A hierarchy of techniques available to characterise climate variability with increasing level of effort, to be applied when risks to supply system performance due to climate variability are higher, is indicated in Figure 8. The threshold for applying each technique is subjective. However at the current time, major capital cities and some regional cities in Australia and New Zealand are utilising stochastic data generation, paleoclimate reconstructions, or paleo-stochastic data generation. To date, the level of effort to use these techniques has limited their application outside of these areas. Enabling projects, such as the creation of stochastic or paleo-stochastic datasets across all of New South Wales (DPE, 2023), will reduce the level of effort involved for water service providers with smaller at-risk supply systems. Further details about stochastic data generation are provided in Section 4.8.

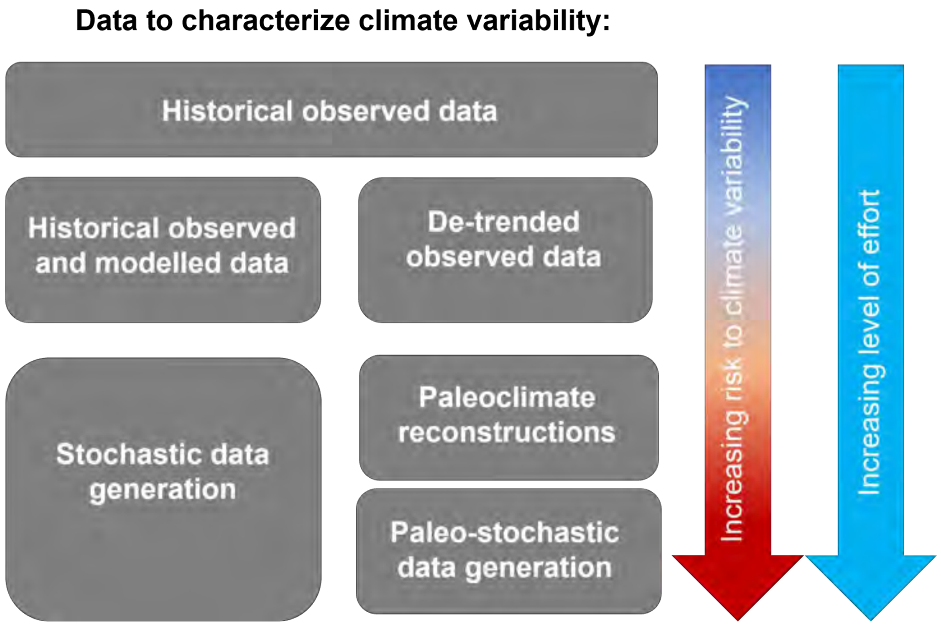

Figure 8 Approaches to characterising climate variability

Length of climate record to adopt: For systems at lower risk of poor performance due to climate variability, historic climate variability, as observed in the historical climate or streamflow record, may be adequate to suitably assess those risks. For a supply system largely or fully supplied from climate independent water sources, there is little value in expending great effort to characterise climate variability, beyond that readily available from the historic climate record.

Given the nature of climate cycles historically, typically several decades of hydroclimate information are required to reasonably understand climate variability. McMahon and Mein (1986) provided a simple example of this for streamflows of different levels of variance, as shown in Table 13. To reduce the standard error of estimate of the mean annual flow to within 5%, up to 100 years of data would be required for streams of low variability ($C_v \leq 0.5$). Up to 400 years of data would be required for streams of high variability ($C_v=1$).

Table 13 Minimum lengths of record (years) to estimate mean annual streamflow (based on McMahon and Mein (1986))

Coefficient of variation, C_v	**Minimum length of record for standard error ≤ ± 5%**	**Minimum length of record for standard error ≤ ± 10%**
0.3	36	9
0.5	100	25
0.7	196	49
1.0	400	100

The possibility of more severe droughts: The historical instrumental record provides only a small snapshot of climate variability. This is supported by paleoclimate reconstructions which indicate, for some regions, previous dry periods of longer duration than those observed historically (e.g. Ho et al., 2015). Verdon-Kidd and Kiem (2009) demonstrated that the climate conditions that led to south-east Australia's three major droughts were all different. This suggests that other more severe droughts than those observed historically are entirely plausible.

Suitability of paleoclimate information: Paleoclimate reconstructions are reconstructions of rainfall, or more commonly, reconstructions of climate indicators of rainfall (e.g. ENSO or the IPO) over past centuries, as interpreted from paleoclimate proxy records. These proxy records are various non-climate sources, such as tree ring widths, ice cores, stalactite growth, coral growth, etc. Paleoclimate reconstructions can help to better understand historical climate variability over past centuries, including the frequency and duration of drier periods, relative to those observed in the instrumental record. These reconstructions infer climate conditions prior to climate data being recorded. The accuracy and therefore suitability of using paleoclimate reconstructions depends upon the quality of the paleoclimate signal in the proxy record, and the strength of the links between the paleoclimate signal and local climate conditions. This is known to vary across Australia (Ballis, 2018). The suitability of paleoclimate proxy records is high, for example, in Queensland where coral records provide a high quality indicator of local climate conditions. In contrast it is low across much of southern Australia, where previous studies have been unable to generate paleoclimate reconstructions of adequate quality. A summary of paleoclimate information available for New Zealand including a list of references can be found at NIWA (2023). A summary of paleoclimate proxy records available for Australia, including correlations with climate in regions of Queensland can be found at Queensland Government and Seqwater (2023).

Recently, the NSW State Government with support from the University of Adelaide has generated paleo-stochastic datasets (DPE, 2023). The model parameters in a stochastic climate data model fitted to the historical instrumental climate record have been modified to reflect differences in the persistence of being in either a positive or negative phase of the inter-decadal pacific oscillation, as informed by the paleoclimate proxy records relative to the instrumental climate record. Such an approach combines both stochastic data generation and paleoclimate reconstructions to maximise the available information about climate variability.

Value of climate independent water sources: Where a supply system is wholly supplied from climate dependent water sources, having access to a climate independent water source can improve the robustness and resilience of the supply system to climate variability. It can also offer an enduring supply during drought. The value of this is increased reliability of supply during drought, potentially significantly mitigating climate risks to water availability. The higher the proportion of water available from climate independent water sources, the higher the reliability of supply will typically be. The value for money of investing in climate independent water sources in any location still must be assessed. This is because they are often a higher cost water source, particularly for inland areas without feasible access to seawater desalination.

Future research and investigations:

Table 14 Future research and investigation to support ongoing improvement and understanding of climate variability

Research and investigation area R3: Improved paleoclimate information: Continued research into paleoclimate reconstructions to improve their quality, and temporal and spatial coverage.
Research and investigation area R4: Climate variability under climate change: Continued research into our understanding of how the characteristics of extreme drought may or may not change under projected climate change.

4.7 Water resource planning models

What is it? Water resource planning models estimate water availability and use, typically over time scales of many decades, under different scenarios. Various tools and platforms can be used for this purpose.

Why is it relevant to urban water resources planning? Water resource planning models provide valuable information to support urban water resource planning decision making. Relevant principles are listed in Table 15 and discussed below.

Table 15 Water resource planning principles for water resource planning models

Title	Principle
PM-1: Models for decision support	Water resource models are decision support tools, not decision-making tools.
PM-2: Modelling platform(s)	The modelling platform to adopt should be informed by various considerations, most importantly whether it is fit-for-purpose for the local application.
PM-3: Model complexity	The level of detail and time step of a model should be sufficient to assess supply system performance. Sometimes a less complex urban water resource model could provide greater insights than a more complex model, because of the ability to explore more scenarios and response options with that simpler model.
PM-4: Fit for purpose water supply models	When modelling fit-for-purpose water supplies for drinking and non-drinking water uses, using representative, high detail, fine scale models to conceptually inform lower detail, large scale models currently offers the best combination of modelling accuracy and efficacy. This may change as hardware and software improves.

Discussion of principles:

Models for decision support: Water resource models provide valuable information to support decision making. However, as discussed further in Section 7.3, decisions are made by humans interpreting model outputs, not by the model itself. This includes consideration of aspects of supply system performance that are not modelled.

Modelling platform: Various modelling platforms are available to use, each with their own pros and cons (WREMA, 2020a). The choice of modelling platform should be informed primarily by whether it is fit for purpose for your application (e.g. the ability of the platform to adequately represent the important elements of your supply system and to generate the performance metrics of most interest for your supply system). This is followed by the familiarity of users within your organisation with the platform, the level of support available both from the platform provider and other modellers, and the licensing fees.

eWater's Source modelling platform has been adopted as Australia's national hydrological modelling platform as part of Australia's National Hydrological Modelling Strategy (NWRC, 2022). Many water service providers are using modelling platforms other than the Source because of their specific functionality or ease of use. Other reasons include the significant cost to transfer to a new modelling platform, and the existence of legacy decision making and existing operations linked to other modelling platforms.

Notably, the WATHNET platform continues to be used by several of Australia and New Zealand's major urban water service providers. This has been influenced by its innovation in urban water resource applications, particularly in the area of stochastic data generation and modelling, and optimisation. The water sector continues to engage with eWater to develop enhancements to Source. While there are state-based groups that support the use of Source, for example the Victorian Hydrological Modelling Group, there would be significant benefit in forming a national modelling community of practice to support water service providers who use Source.

Various other models may be more fit-for-purpose for some supply systems, either in place of or in addition to water resource models such as Source and WATHNET. These include groundwater models for supply systems predominantly sourced from groundwater, various types of demand models, rainfall-runoff models, models of intercepting activities, water quality models, integrated water management models, or purpose-built scripts and spreadsheets.

Model complexity: The level of model complexity should be aligned with the ways in which the model will be applied. A highly discretised daily timestep model may not be required for bulk water planning, but may be vital for accurately representing the delivery of environmental flows. The degree of modelling complexity can also influence its use. Highly complex models are likely to represent observed behaviour more accurately. However the more complex a model becomes, the longer it takes to run, the more effort it takes to maintain, and the more prone it can be to input uncertainties. For supply systems where the number of input scenarios is likely to be high, consideration can be given to adopting a simpler supply system representation (Fowler et al., 2022). The principles for such an approach in Fowler et al. (2022) included:

i. considering the behaviour response time of the supply system to identify whether longer time step modelling could achieve the same level of accuracy for performance metrics as shorter time step modelling (e.g. for systems with large storage capacity relative to inflows and demands); and
ii. considering the correlation between model inputs to assess whether they can be lumped into homogenous inputs.

Model simplifications are only appropriate where they do not compromise the ability to assess supply system performance. Reducing system complexity can have unintended consequences if essential elements of the supply system representation are not considered.

This can particularly be the case when using optimisation, such as for hydro-economic modelling of urban water supply systems, noting that computing power available locally and via cloud computing, continues to increase.

Model simplification has previously been used for hydro-economic modelling. Hydro-economic models incorporate financial information into water quantity models, such as unit costs for supply system operation, so that operation can be optimised for both water resource objectives and operating cost at the same time. It can also include capital costs associated with a supply system augmentation, when considering alternative supply portfolios. Hydro-economic modelling has also been applied to optimise trade-offs between the cost of supplying water versus the cost of not supplying water. This has been done by incorporating a financial estimate of the cost of water restrictions (e.g. Purves et al. (2015)). In such an approach it is noted that outcomes can be sensitive to the assumed financial cost of restrictions, which can have a high degree of uncertainty.

Any model used in water resource planning should have its validity verified against recent observed behaviour, wherever observed data allows this. Guidance for good practice modelling is available from eWater (2016). An example of assessing the impact of water resource model parameter uncertainty on performance objectives can be found in Berghout et al. (2017).

Fit for purpose water supply models: Modelling integrated water supply systems with different source and demand water qualities can be complex. Modelling large, fully integrated supply systems with supply sources available at different spatial scales, different temporal scales, and of different water qualities, is still evolving. Using representative, high detail, fine scale models to conceptually inform lower detail, large scale models is a good way to combine modelling accuracy and efficacy. This may change as hardware and software improves. The temporal and spatial scales for different types of water resource models are not directly compatible.

Daily or sub-daily time step modelling is required at a lot-scale or neighbourhood scale for many integrated water management applications. This finer detailed modelling is typically undertaken over short, representative climate periods due to long model run times. Directly integrating individual lot or neighbourhood scale modelling, covering the whole supply network, into bulk water resource models can require a high computational effort. In contrast, bulk drinking water supply is often modelled at daily or monthly time steps, with demands aggregated to supply areas with many water customers. Embedded within those bulk water demand models will be an assumed historical use from non-drinking water sources. Where supply from those non-drinking water sources is expected to change over the planning horizon, such that it would significantly influence per connection use from the drinking water system, then an adjustment to bulk water demand models could be required. Alternatively the non-drinking water source could be explicitly represented in the bulk water resource model.

Future research and investigations:

Table 16 Future research and investigation to support ongoing improvement and understanding of climate variability

Research and investigation area R5: National community of practice for Source: The creation of a community practice for water service providers who use Source, to share knowledge and experience of its use for water resources planning.

There are communities of practice for Source modelling that exist in some jurisdictions, but these do not capture all water service providers who may be using Source. This can limit the ability to share knowledge with other Source modellers beyond State and Territory borders.

4.8 Stochastic data

What is it? Stochastic data are random numbers that are modified so that they have the same statistical characteristics (in terms of mean, variance, skew, long-term persistency, etc.) as the reference period data on which they are based (adapted from Srikanthan et al., 2007). The instrumental climate record represents one realisation of many possible realisations of climate, which could occur if the sequencing of that climate were to unfold differently. Stochastic models are typically used to generate alternative sequences of climate, streamflow and/or demand. Stochastic modelling has historically been undertaken by academics, researchers, and specialist consultants, however stochastic data generation models have now been incorporated into commonly used water resource modelling software, such as Source and WATHNET.

Stochastic models fitted to streamflows and demands remove the influence of rainfall-runoff model and demand model uncertainty, but do not allow climate perturbations associated with projected climate change to be run through the stochastic models. Generating stochastic climate data rather than stochastic inflow, demand or recharge data allows climate change impact assessments to be more readily undertaken.

The model form will influence the extent to which statistics from the reference dataset are preserved at daily, seasonal, annual, and multi-annual time scales, as well as the preservation of cross-correlation of dependent datasets (e.g. making sure that rain generated at one location occurs on the same days at other locations, if the rain at these different locations was highly correlated in the reference dataset). When considering the stochastic model form, preserving annual persistence of inflows will be more important in supply systems with multiple years of storage than supply systems with single year storages. Preserving cross-correlation between climate variables will be more important in supply systems where temperature and evaporation variability have a more significant influence on supply system performance in addition to the influence of rainfall variability.

Why is it relevant to urban water resources planning? Stochastic data informs the uncertainty of supply system performance generated from the instrumental climate record alone. It can also be used to estimate the properties of lower likelihood climate events than those observed historically, noting that these estimates become less reliable for very low likelihood events. Guidance on when to consider the use of stochastic data was contained in the discussion of climate variability (see Section 4.6).

Relevant principles are listed in Table 17 and discussed below.

Table 17 Water resource planning principles for stochastic data

Title	Principle
ST-1: Very low likelihood event plausibility	Stochastic models of climate are mathematical models, not physical process-based models. Extreme values of very low likelihood that are generated from stochastic models are not necessarily a physically plausible representation of climate behaviour.
ST-2: Informing uncertainty	Stochastic models are arguably best used to inform uncertainty around an estimate of supply system performance generated using a reference input sequence, when that supply system is subject to hypothetical alternative input sequencing.
ST-3: Reference data quality and length	A poor quality input data set will result in a poor quality stochastic data set. Reference data set length should be sufficient to capture key, persistent droughts.

Discussion of principles:

Very low likelihood event plausibility: Stochastic models of climate are mathematical models, not physical process-based models. Extreme values of very low likelihood that are generated from stochastic models are not necessarily a physically plausible representation of climate behaviour. Stochastic model outputs reflect the properties of a reference dataset. Where the length of that reference dataset is “X” years, event likelihoods from that stochastic data that are extrapolated well beyond the 1 in X annual exceedance probability are likely be of low confidence. This is demonstrated when the outcomes of stochastic models, informed by the instrumental climate record, are compared against paleoclimate reconstructions or paleo-stochastic models that are informed by both the instrumental climate record and paleoclimate proxy records. The recent paleo-stochastic data generation exercise by the NSW State Government confirmed that stochastic models informed by paleoclimate proxy records can generate different outcomes than those informed by instrumental climate data alone.

Informing uncertainty: Stochastic data can be generated as a single long sequence, or divided into replicates of length equal to the reference dataset used to inform the stochastic model. The advantage of adopting a single long sequence, particularly for supply systems with long system memory in storage, is that is preserves storage memory over the model run period, and allows event likelihoods to be generated that are lower than those over the reference dataset (albeit with low confidence at very low likelihoods).

Adopting replicates of length equal to the reference dataset allows an estimate of uncertainty to be placed around the supply system performance metric values generated over that reference dataset. For example in Figure 9, it can be seen that stochastic data provides an uncertainty distribution around a single estimate of urban supply system yield (based on the instrumental record only), when utilising stochastic replicates that are of comparable length to the instrumental record. Analysis of stochastically generated synthetic sequences can be used to support, and provide context to, analysis of a reference climate sequence, rather than as a replacement of it. The synthetic data generated does not produce a "better" estimate of performance compared to that produced using a single input sequence. Stochastic data provides insight into the likely impacts of more extreme synthetic droughts, and insight into the likely distribution of system performance given the uncertainty due to climate variability.

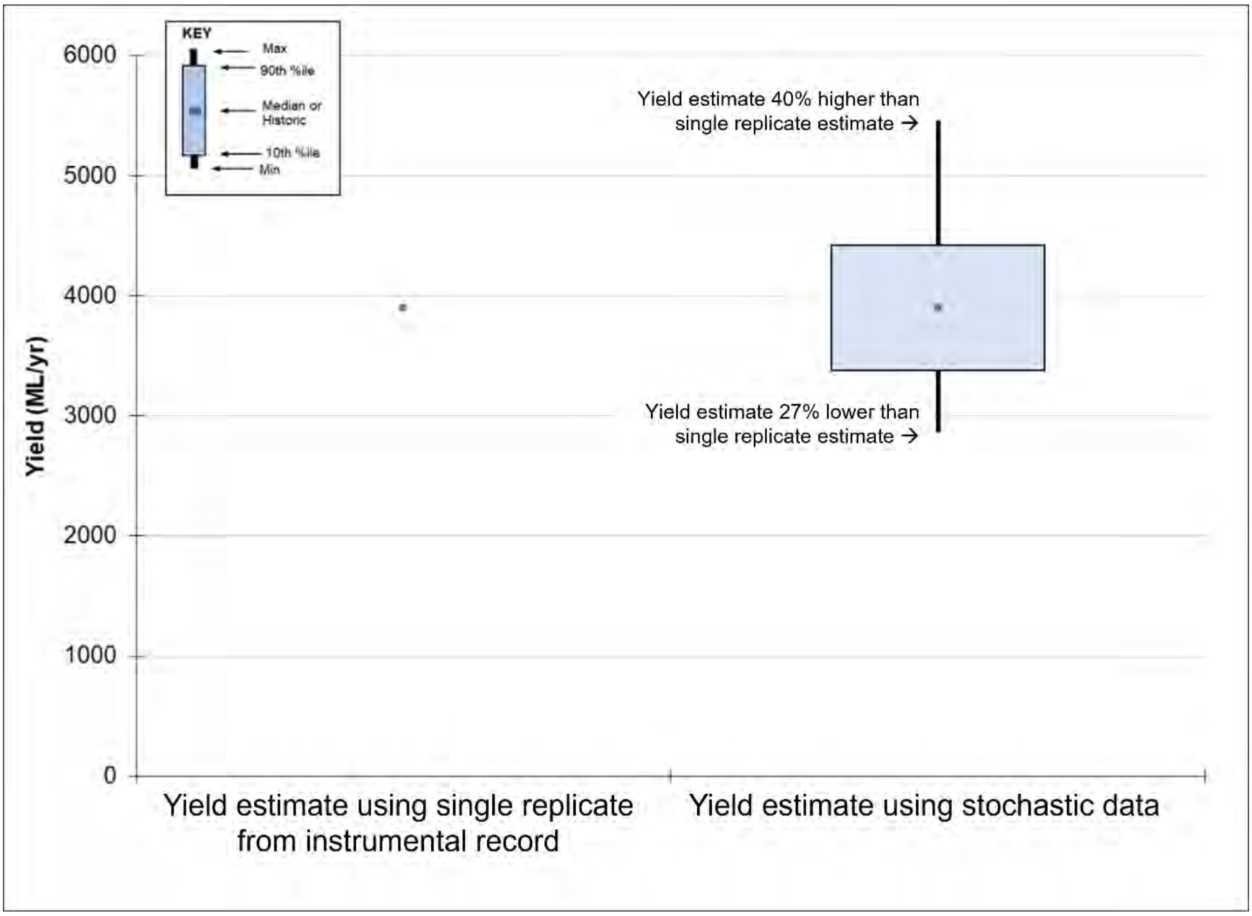

Figure 9 Illustration of the potential distribution of a yield estimate using stochastic data, relative to a single estimate informed only by the instrumental record (adapted from DPE Water unpublished report)

Reference data quality and length: The choice of reference dataset period and length are important, including its quality, stationarity, and its representativeness of broader climate variability. If only a short reference dataset is used, then the stochastic model behaviour will be limited by the information contained within that reference dataset.

Future research and investigations:

Table 18 Future research and investigation to support ongoing improvement and understanding of stochastic data

Research and investigation area R6: Value of stochastic data for smaller supply systems: To date, stochastic data has been used to characterise urban supply system behaviour for larger supply systems. The practical value for smaller supply systems is yet to be fully tested and should be confirmed through case studies.
Research and investigation area R7: Application-ready stochastic data: Government agencies should develop application-ready stochastic climate datasets for all of Australia and New Zealand, as has recently been undertaken for all of New South Wales.

4.9 Optimisation

What is it? Optimisation is the process by which a set of operating rules or a supply system configuration, which best meet performance objectives, can more rapidly be identified.

Why is it relevant to urban water resources planning? Mathematical optimisation can help to identify a solution (or a subset of solutions) more quickly, when manual exploration of those potential solutions would require too much time and effort. Relevant principles are listed in Table 19 and discussed below.

Table 19 Water resource planning principles for optimisation

Title	Principle
OP-1: When to use optimisation	Mathematical optimisation of supply system operation or configuration should be considered where the number of available choices is too large to manually explore.
OP-2: Decision support not decision-making	Optimisation is a decision support tool, not a decision-making tool.

Discussion of principles:

When to use optimisation: Mathematical optimisation is best applied where there are many decision variables (i.e. parameters which can be adjusted), but few performance objectives, and the time and effort to manually explore all possible decision variables is computationally infeasible. In an urban water supply system, optimisation can be applied to operating rules or to the selection of a water supply portfolio, or both. Optimisation works by testing a subset of possible decision variables, assessing performance (referred to as the objective functions) with those possible decision variables, subject to certain decision constraints. Key to successful optimisation is the ability to mathematically represent the performance objectives (referred to as objective functions). Optimisation can be computationally intensive, particularly for large, complex supply systems, when consideration can be given to simplifying model representation. Replicate thinning can also be undertaken, where different input replicates contain very similar information, to reduce model run times.

Decision support not decision-making: Like any modelling, optimisation generates outcomes that inform decision-making, but it is not a decision-making tool. This is because there are always likely to be considerations for decision-making that lie outside of what it is possible to model. Using different optimisation algorithms, different decision variables, and different seed values and constraints for those variables can lead to different “optimised” solutions. Given these considerations, it is important to sanity check the outcomes of any optimisation exercise, to ensure that the mathematically optimal solution makes sense, and can be implemented. This may require further testing and monitoring of the outcomes of the optimisation in practice. Optimisation has been applied to several major urban water supply systems, most commonly using a technique known as multi-objective pareto front optimisation, described further in Section 7.2. Refer to Kularathna et al. (2011) or Mortazavi-Naeini et al. (2015) for example applications of optimisation of water supply system operating rules and portfolios.

4.10 Data availability and quality

What is it? The availability and quality of data collected for use in urban water resource planning.

Why is it relevant to urban water resources planning? Garbage in = garbage out. The availability and quality of data will influence the defensibility of decision making informed by that data. Relevant principles are listed in Table 20 and discussed below.

Table 20 Water resource planning principle for data quality

Title	Principle
DQ-1: Investment in data collection	Where practical and feasible, investment should be made to improve data availability and quality where poor data availability and quality currently inhibits decision making.

Discussion of principles:

The WSAA (2023) Water Sector Data Playbook runs through strategies for collecting, storing, and quality assuring water service provider data. Some particular aspects of relevance to urban water resources planning include the following.

Quality assurance: The data collected should be quality assured by reporting on the conditions under which the data was collected (e.g. using standardised quality codes or specific notes on the data), then visualising the data as it is collected to quickly identify any deviations from historical behaviour that may be due to data error. Undertaking quality assurance only when the data is used for urban water resources planning, which might be at intervals of several years, can often be too late to correct data errors. These errors could have been identified and resolved at or shortly after the time of collection.

Measurement error: All data will have an associated measurement error. Ideally, any measurement errors will be unbiased over time, with measurement error on individual data points randomized. For many variables, measurement error can however increase at extreme values. Notably for streamflow measurements, measurement uncertainty is typically higher for very high flows, and for very low flows outside of the range of gauged streamflows in the site's rating table. Data uncertainty will be different for different parameters, or for the same parameter at different locations. Having a basic understanding of the uncertainty of different datasets will help to identify where trust in that data is best placed, when those datasets are in conflict.

Sensitivity testing: Sensitivity testing can identify which input datasets a given performance metric is most sensitive to. This could include, for example, using spider plots that show for a given input perturbation, by how much the performance metric would change. High data uncertainty is less important where the sensitivity of performance metrics to an input variable is low.

Investment in data collection: Where practical and feasible, investment should be made to improve data availability and quality where poor data availability and quality currently inhibits decision making.

5. UNDERSTANDING YOUR WATER SUPPLY NEEDS

5.1 Performance metrics

What is it? Supply system performance metrics characterise the performance of a supply system.

Why is it relevant to urban water resources planning? Supply system performance is a key indicator to inform water resources planning, particularly when assessed as changes over time, or under different input conditions, or relative to a performance standard. Relevant principles are listed in Table 21 and discussed below.

Table 21 Water resource planning principles for performance metrics

Title	Principle
ME-1: Metrics to consider	Measures of supply system performance traditionally include yield, reliability of supply, and cost. More holistic measures of performance also include liveability and sustainability, as well as the robustness of all performance metrics.
ME-2: Yield vs reliability	Yield is better suited as a performance metric where level of service objectives are known, agreed, and unlikely to change. Reliability of supply is better suited as a performance metric when exploring many level of service options. It can also be better suited to assessing the performance of supply systems with non-stationary inputs and large storage capacity relative to water source availability and demand, in systems where changes in demand magnitude have little or no impact on yield, and for hydro-economic modelling.

Discussion of principles:

Metrics to consider: Performance metrics should ideally be SMART, i.e. specific, measurable, achievable, relevant, and time-bound. Performance standards attached to those metrics should be by agreement between a water service provider and its stakeholders, notably customers and government regulators.

The relevance of a metric will depend on the audience for whom the metric is being prepared. Metrics can be related to adhering to a process (e.g. has an urban water resource plan been prepared?) or to generating an outcome (e.g. yield or reliability of supply). Metrics about adhering to a process (e.g. those in Aither (2021)) are typically of most benefit to regulators monitoring many water service providers. Those metrics about generating an outcome are typically of most benefit to customers for their specific supply system. Within this urban water resources planning framework, adhering to process is covered by the principles outlined throughout this document, and by the checklist of actions in Section 8. The following text discusses metrics related to generating an outcome.

Measures of supply system performance traditionally include yield, reliability of supply, and cost. More holistic measures of performance also include liveability and sustainability, as well as the robustness of all performance metrics.

Cost is a measure of the cost of building and operating a supply system. This can be expressed as a net present value or other equivalent financial metrics, or as change in customer prices. Change in customer prices is harder to generate because it requires a financial model to convert net present values into a change in customer bills.

Liveability recognises the social value of water for maintaining green and blue space, with its associated health and wellbeing benefits, such as reducing urban heat on days of extreme heat. Liveability can also extend to specific recreational values associated with water supply system operation, or downstream flood risks. Tools have been developed that quantify indicators of liveability, such as changes in air temperature in urban heat islands, or the total area of green space in an urban area under a given climate event (e.g. Pfausch et al, 2023).

Metrics of sustainability will be specific to the supply system, but could include the amount of greenhouse gas emissions, or the ability to meet environmental objectives for freshwater ecosystems, or groundwater dependent ecosystems. For groundwater systems, sustainability can be measured by the ability of extraction to not exceed average annual net recharge. Mining of groundwater resources is not sustainable – in this situation relative measures of sustainability could be helpful for decision-making, such as the remaining duration of supply in years or the remaining volume or proportion of the resource remaining at a given point in time.

Case study: Greater Western Water performance metrics

Greater Western Water (GWW) provides water and wastewater services across Melbourne and its rapidly expanding western region, from the CBD to the Macedon Ranges. GWW originally explored sustainable pathways for management and effective use of sewage and recycled water within our service area. A growing population, declining surface water resources due to climate change and Government policy to return water to the environment and Traditional Owners led to the project to consider all relevant water cycle elements. This also led to an expansion of the project to consider and to work collaboratively with other overlapping projects in a wider region. Modelling included streamflow, reservoirs, demands from river systems, wastewater generation, and recycled water usage. The modelling has allowed development of adaptive pathways that enables an understanding of option interdependencies and a whole of catchment approach that may unlock broader system benefits and costs, particularly larger avoidable costs. The project is now exploring the potential cost savings, net present value, and the knowledge, value and rule (KVR)[3] gaps for each of the adaptive pathways.

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[3] See Colloff et al. (2018) for further explanation of the values-rules-knowledge approach for challenging decision-making assumptions

Yield versus reliability: Yield is the volume of water that can be supplied from a supply system at a given level of service, subject to assumed operating rules and patterns of demand. It is typically expressed as the average annual unrestricted demand that can be supplied at a given level of service, for direct comparison against current and projected average annual unrestricted demands.

Reliability of supply is typically defined by an annual (or monthly) likelihood of reaching a given supply system condition, but can also include the duration for which that condition is reached. Historically, reliability of supply has been linked to the likelihood of any water restrictions, the likelihood of severe water restrictions, and the likelihood of not reaching a minimum operating level or reserve volume. It could equally apply to the likelihood of having to use a higher cost water source. Severe restrictions are defined by agreement based on the likely impacts on customers from those restrictions. The duration of restrictions may also be an important metric for some communities where a short duration of restrictions can readily be tolerated without appreciable impact, but a long duration of restrictions cannot.

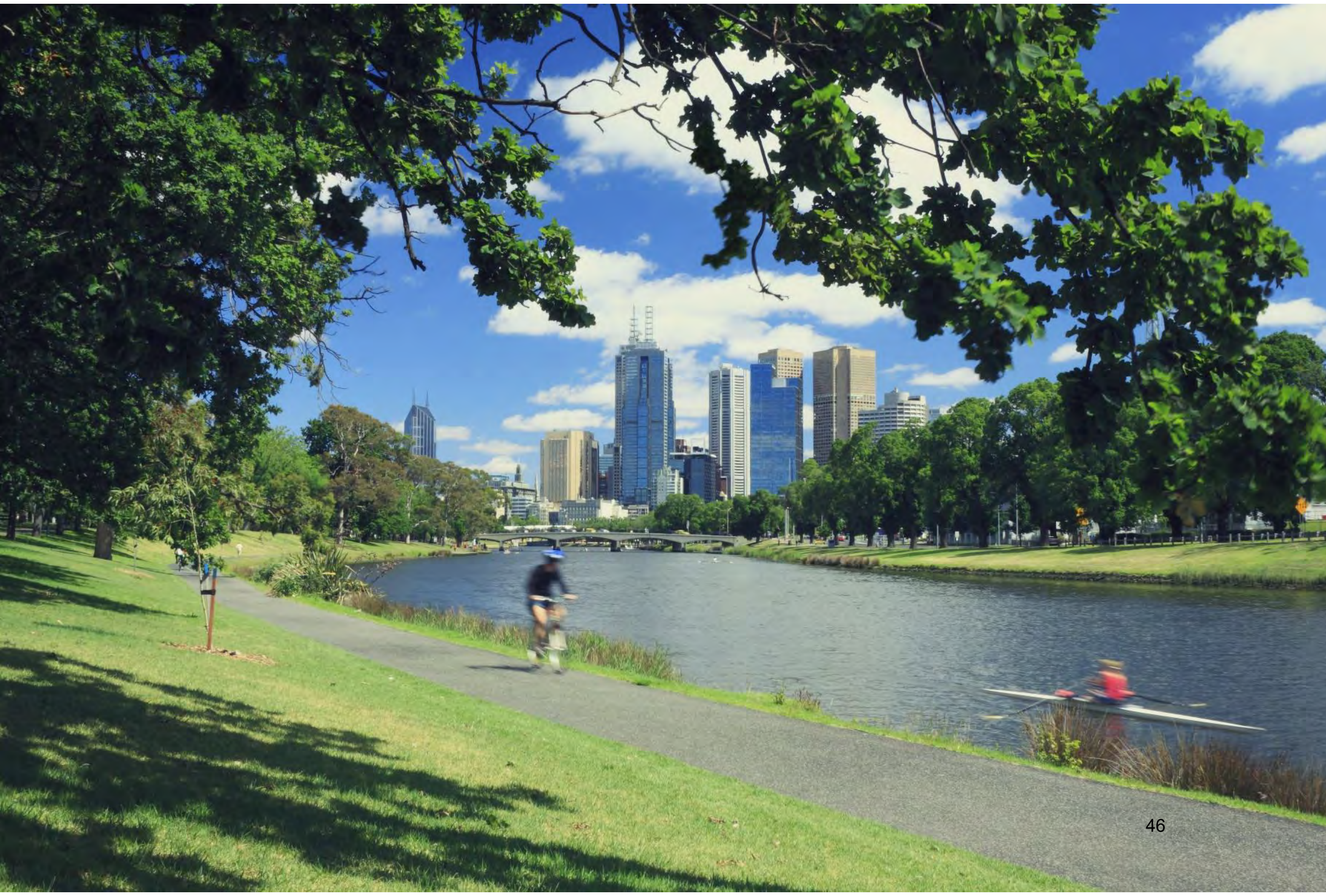
Reliability of supply is typically estimated in two different ways:

i. Over time (e.g. an X% likelihood, or as a likelihood of Y years in 10, or Z years in 100). This approach has typically been applied when estimating reliability of supply from a single climate sequence;
ii. Across replicates or scenarios at a given point in time (e.g. an X% likelihood in year 2030, a Y% likelihood in the year 2040, etc.). This approach has typically been applied when using multi-replicates or stochastic data where supply system behaviour is projected forward from a current supply system condition. In this example, the X% and Y% represent the percentage of replicates or scenarios in which a given condition is reached.

Yield and reliability have generally been used interchangeably, but they do have specific advantages and disadvantages. Assessing yield over time has the advantage that it allows a direct comparison against projected demand, which is visually powerful for decision-making. However it assumes a fixed level of service that is always implied within that yield estimate, and sometimes overlooked or forgotten by decision makers. Yield is assessed on average, over the long-term, and is generally predicated on a given level of demand at any point in time over the planning horizon.

Reliability of supply, when assessed, is not attached to a specific level of service. This makes it well suited to applications where alternative levels of service, and the implications of adopting them, are being explored. Where reliability of supply is defined by several metrics (e.g. the frequency of mild restrictions and the frequency of severe restrictions), the performance of those metrics can be presented separately and transparently. Reliability of supply assessment also has specific application for supply systems with non-stationary inputs and large storage capacity relative to water source availability and demand (see Section 4.7). It is also applicable in systems where changes in demand magnitude have little or no impact on restrictions, and for hydro-economic modelling where a financial cost is assigned uniquely to different states of operation.

Demand and reliability (and yield) are not always dependent. For supply systems with performance measures related only to water source availability, the level of demand will not affect performance. For example, where a supply system has its water restriction triggers based on streamflow upstream of its offtake, then the frequency of restrictions (i.e. the performance measure) will be unaffected by the level of demand. In this situation, yield will be defined by the reliability of the water source only. In contrast, if a supply system has its water restriction triggers based on volume in storage, then the frequency of restrictions will also be affected by the level of demand.



5.2 Performance standards

What is it? Supply system performance standards specify the minimum level that should or must be achieved.

Why is it relevant to urban water resources planning? Performance standards provide direction to water service providers about the extent to which a supply system meets customer and community expectations, and allow the costs and benefits of different water supply planning options to be compared. Relevant principles are listed in Table 22 and discussed below.

Table 22 Water resource planning principles for performance standards

Title	Principle
PS-1: Primary performance objective	Maintaining a minimum water supply for critical human water needs at an acceptable level of risk and at an acceptable water quality is the primary objective of an urban water supply system.
PS-2: Planning for critical human water needs	If it is unacceptable to not maintain a minimum supply for critical human water needs, then there should always be a plan in place to provide that supply.
PS-3: Standards by agreement	Setting performance standards for water resource availability is by agreement with customers and government regulators. The performance standard should reflect the level of risk associated with not meeting that standard.
PS-4: Measurability of standards	The likelihood of a performance standard should not be lower than that which is measurable using available information and models.

Primary performance objective: Maintaining a minimum water supply for critical human water needs at an acceptable level of risk and at an acceptable water quality is the primary objective of an urban water supply system. Whilst other performance objectives exist, they are always secondary to this need. The definition of critical human water needs and its associated volume will be unique to each supply system and community. It includes in-house water use for drinking and sanitation, and can extend to commercial, industrial, and essential municipal water uses. For example, water for power generation so that the electricity supply can be maintained, or water supply for manufacturing so that large numbers of people do not lose their jobs. It is sometimes associated with that portion of demand that would be unaffected by the most severe water restrictions available in a given supply system. The term critical human water needs is used in some, but not all jurisdictions, and its definition will be unique to the particular supply system. An alternative term used with similar meaning is the essential minimum supply volume. Where critical human water needs include supplying water to elements of the economy beyond basic in-house water for drinking and sanitation, the minimum volume for drinking and sanitation should still be specified separately. This allows it to be separately accounted for in the event of a dire water supply emergency.

Planning for critical human water needs: If it is unacceptable to not maintain a minimum supply for critical human water needs, then there should always be a plan in place to provide that supply. Any performance standard should consider the minimum performance that the supply system should provide in the event of a severe supply reduction. This could involve defining critical human water needs for various purposes (in-house residential water uses, industrial and commercial water uses, etc.), and the likelihood or duration for which those critical human water needs would be provided. This can include a plan for an enduring supply that is not subject to climate risks.

Standards by agreement: Beyond this minimum requirement, standards for reliability of supply vary in different jurisdictions and for different towns and cities. There is no universally adopted minimum performance standard for reliability of supply for urban water supply systems in Australia and New Zealand. For example, in regional Victoria, level of service objectives have typically been set for a 1 in 10 annual likelihood on average over the long-term of not requiring water restrictions, with a 1 in 15 annual likelihood of not requiring severe water restrictions, and a less than 1 in 100 annual likelihood for failure due to drought (e.g. NEW, 2022, where failure was defined as reaching a minimum operating level). For capital cities in Australia and New Zealand, standards for failure due to drought are typically much more stringent. Internationally, the United Kingdom (Environment Agency et al., 2023) has specified a 1 in 500 (0.2%) annual likelihood for failure due to drought (where failure is defined by a request to breach environmental obligations).

A performance standard for one supply system will not automatically be applicable to other supply systems. Setting performance standards for reliability of supply will be a function of community preferences with regards to risk appetite and risk aversion, which will be influenced by:

- The consequences of not meeting those performance standards, which in turn will be dependent on the number of people affected and whether industries of State or national significance would be affected;
- The desire for consistency in minimum standards across supply systems managed by the same water service provider, due to perceptions of inequality if those standards are different;
- The availability of contingency supply measures and enduring supply to meet or partially meet critical human water needs, which can mitigate or obviate those consequences; and
- The ability of water users to temporarily reduce their demand on the supply system, through fit-for-purpose demand substitution with supply from non-drinking water sources, and by reducing water use (voluntarily or mandated).

Setting performance standards for water resource availability is by agreement with customers and government regulators. The performance standard should reflect the level of risk associated with not meeting that standard. When reviewing performance standards, there can be a role for government regulators to ensure that there has been a process of effective engagement with the community to set those standards.

More stringent standards are typically put in place:

i. for larger population centres
ii. for supply to industries of State or national significance, and
iii. where the consequence of not meeting that standard affects the ability to maintain a minimum agreed water supply (as opposed to just incurring a higher cost to maintain that supply).

Measurability of standards: Standards for reliability of supply are intrinsically linked to the hydro-climate assumptions used to assess behaviour against them. Setting standards to not draw down storages to minimum operating levels under a repeat of the worst design drought will depend on how the design drought was derived. For example, whether that design drought is based on observations over the historical streamflow or groundwater level record, the historical climate record, from paleoclimate proxy records, or from stochastic data. The performance standard being set should be capable of being assessed with the available modelled data. For example, a performance standard to not reach minimum operating levels for a drought with a 1 in 1000 annual exceedance probability cannot be assessed against when using a 130-year instrumental climate record. Further comments about the use of stochastic data to inform performance objectives associated with very low likelihood events are presented in Section 4.8.

Bringing these metrics together for decision making is discussed further in Section 7.2 and 7.3.

Future research and investigations:

Table 23 Future research and investigation to support ongoing improvement and understanding of stochastic data

Research and investigation area R8: Existing performance standards: A catalogue of existing performance standards for urban water supply systems in Australia, New Zealand, and internationally. This should include the rationale that led to those standards being adopted.

5.3 Community consultation and input

What is it? Community consultation can involve various engagement strategies. These include direct consultation with water users during water resource planning activities, regular engagement with customer consultative committees, and providing ongoing opportunities for the community to provide input and feedback to water service providers.

Why is it relevant to urban water resources planning? Water supply systems exist to provide water to the community. The community pays for these supply systems, and individual water users can be directly affected by the urban water resource planning decisions made by water service providers. The planning and operation of these supply systems should therefore reflect customer appetite for risk, and expectations for the performance of the supply system, its cost, and the broader impacts of its design and operation. Relevant principles are listed in Table 24 and discussed below.

Table 24 Water resource planning principles for community consultation and input

Title	Principle
CO-1: Consultation is good practice	Community consultation is an essential element of good practice urban water resources planning.
CO-2: Ongoing education	Ongoing education about water resources planning will improve water literacy amongst the community, allowing the community to participate in water resource plan development more effectively.
CO-3: Tailor your engagement	Each water service provider will be best placed to decide on its preferred community engagement strategy.
CO-4: Don’t wait for a crisis to talk	Water service providers should not wait for a crisis to talk to the community about urban resources planning

Discussion of principles:

Consultation is good practice: Most water users are not climate scientists, hydrologists, hydrogeologists, or water resources engineers. Any consultation undertaken with the community should therefore be appropriately pitched in a language that the community can understand, so that they can meaningfully engage with the issues being discussed.

Of primary importance is the community’s input on level of service and any other performance objectives for the supply system. These can be driven by community expectations for supply system performance relative to the community’s willingness to pay for that performance. Water service providers should not hold pre-conceived expectations of community views, other than where they have been informed by previous, directly relevant consultation.

Tailor your engagement: In the area of urban water resources planning, current practice by Australia and New Zealand’s major water service providers typically involves some form of broad community consultation whenever an urban water resource plan is updated. This is usually at a frequency of around every five years, supplemented by ongoing engagement in some form. A process that worked well for one major water service provider involved educating a community group about water resource planning concepts over a 1-2 month period, prior to engaging with them about specific choices to be made about the supply system.

Each water service provider will be best placed to decide on its preferred community engagement strategy. When faced with decisions around setting level of service objectives for water resources, and for selecting preferred water resource planning actions, elements of engagement could include:

- Confirming level of service objectives and any other performance objectives, including which measures of performance are most relevant.
- A statement of current supply system performance, and how that could change under a business as usual scenario.
- Providing an understanding of the likely consequences of reaching certain supply system states (e.g. reaching minimum operating levels in a reservoir) for both the water service provider and its customers.
- Seeking feedback or acceptance on design drought assumptions (risk appetite) used implicitly in testing supply system performance or explicitly in setting performance objectives.
- Identifying particular community or industry groups who could be more affected by particular response options.
- Surveying customers about their option preferences, which could include their willingness to pay to avoid specific responses, or response options that are unacceptable. This could also include identifying community assets for which it would be acceptable to provide a non-drinking water supply.
- Testing the logic for the preferred strategy, including its robustness, any broader community impacts associated with it, and how community input has helped shape the actions adopted.

The level of consultation must be balanced against the possibility of consultation fatigue, when water users may disengage from participation if they are consulted too often. Having a community consultative committee provides the opportunity for ongoing engagement with pre-defined expectations about the level of engagement, however it also risks being unrepresentative if not periodically supplemented with other engagement forums.

Water users are not a homogenous, like-minded group. The community includes, but is not limited to a water service provider’s customers. For example where a planning decision by a water service provider affects landholders who are not their customers, such as when seeking easements for supply infrastructure that run through private rural land. Different views are likely to emerge around levels of service and willingness to pay. Specific interest groups or commercial operators may be uniquely affected by some urban water resource planning decisions, particularly where restrictions on particular water-use activities target those interest groups. It is important that different views can be heard.

Consultation with Traditional Owners / Mana whenua in some regions may require additional time and different engagement approaches, particularly for remote communities. Traditional Owners / Mana whenua can have a long collective memory in their community about climate and water availability. They will have their own specific community objectives, such as around preserving and enhancing connection to ancestral lands.

Smaller water service providers should seek to leverage off the consultation outcomes from larger water service providers, and any relevant WSAA research on community perceptions, where they can reasonably be expected to be applicable locally.

Don’t wait for a crisis to talk: Water service providers should not wait for a crisis to talk to the community about urban resources planning. Regular communication outside of drought provides a greater social licence for water service providers to act with authority during a crisis, knowing that they have already sought community views on the responses they are planning to take.

Ongoing education: Urban water resource planners hold specialist knowledge about urban water resource planning. Communicating that knowledge effectively to stakeholders and the community can sometimes require technical language to be translated into a more widely accessible form. This can include alternative wording, explanatory diagrams, asking technical questions in a different way, or other ways of interacting with people. Communication specialists within or external to water service providers can assist with this.

Ongoing education about water resources planning will improve water literacy amongst the community, allowing the community to participate in water resource plan development more effectively. Where government regulators oversee a water service provider’s water resource planning activities (e.g. financial regulators), targeted or ongoing education about key concepts for urban water resources planning can provide valuable context for those regulators.

Two specific concepts from urban water resource planning that can be difficult for the community to understand are the concepts of yield and reliability. Full definitions for both of these terms are provided in the glossary (Section 10). In essence, yield represents how much water is available to supply customers, and reliability represents the chance that customers will not get all of that water, as shown in Figure 10.

Likelihoods are often difficult for the public to understand, particularly for very low likelihood events. Expressing likelihoods as an average return interval is discouraged, because very unlikely events can occur at any time, and sometimes in quick succession, which can lead to confusing messages about what the return interval actually means. For example, a 1 in 100 year drought could occur twice in a ten year period, which would lead to the obvious question as to why it can be labelled a 1 in 100 year drought. Expressing likelihoods as annual exceedance probabilities as a percentage that is lower than a 1% likelihood (e.g. a 0.1% likelihood or a 0.5% likelihood) are difficult for most people to interpret. However, annual exceedance probabilities can be expressed as a 1 in X chance (e.g. a 1 in 1,000 likelihood in any given year), provided that it is clear that this is an annual likelihood, not an average return interval.

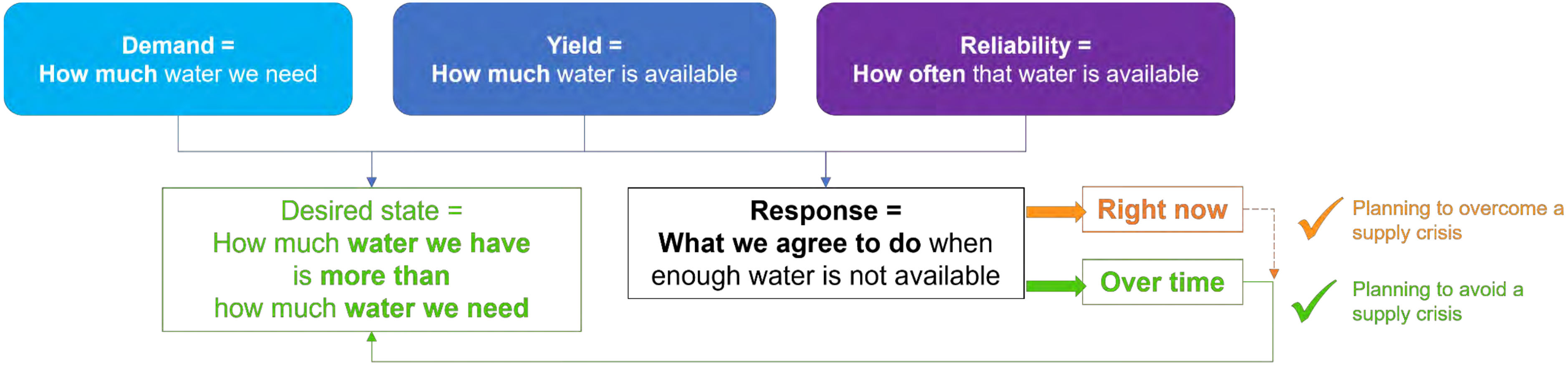


Figure 10 Water resource planning concepts of yield and reliability

Expressing likelihoods as an average occurrence frequency over a period of time can be easier to interpret (e.g. occurring X years in 10 or Y years in 100), but this is also usually more defensible for events of moderate to low likelihood, not for very low likelihoods. For example, a 95% annual reliability of supply could be expressed as providing a certain volume in 95 years out of the next 100 years, with a lower volume expected in 5 of those 100 years. This period of time can be aligned to the planning horizon for an urban water resources plan to provide confidence about the effectiveness of the plan over that planning horizon. For example, if a planning horizon is say 50 years, then reliability of supply can be expressed as an average occurrence frequency of X years over the next 50 years. This assumes that the estimate of reliability of supply takes into account the dynamic changes that could occur over that 50 year period, such as climate change.

Low likelihood events can potentially be related to other low likelihood events that are more relatable, such as the likelihood of your sports team making the finals (i.e. something that might happen every few years on average), the likelihood of your sports team winning the grand final (i.e. something that might happen once every 10 to 20 years on average), or the likelihood of you winning the lotto (i.e. something unlikely to happen in your lifetime, but it could still happen).

6. FUTURE DEMAND AND FUTURE WATER AVAILABILITY

6.1 Future water use

What is it? Future demands for water from the supply system over the planning horizon.

Why is it relevant to urban water resources planning? Future demands for water are a key input and uncertainty for urban water resources planning, and can heavily influence planning outcomes. Relevant principles are listed in Table 25 and discussed below.

Table 25 Water resource planning principles for future water use

Title	Principle
FW-1: A solid foundation	A good understanding of current water use is essential for projecting future water use.
FW-2: Future range of population	Urban water resource planners should consider the possibility of alternative population projections, rather than assuming a single projection is an accurate prediction.
FW-3: Per capita water use change	Per capita (or per connection) residential water use can change over the planning horizon, particularly for new residential developments with access to non-drinking water sources (recycled water, rainwater tanks, etc.), and different housing density.
FW-4: Non-drinking water demand	Projecting both drinking water and non-drinking water demands allows water service providers to more readily seize opportunities for drinking water supply substitution using fit-for-purpose non-drinking water sources.
FW-5: Demand components	Demand components for specific user types (e.g. residential, major industrial use, visitors, rural supply by agreement, non-revenue water) can be separately projected if those components represent a significant proportion of total water demand and/or they are expected to change at a much different rate than total water demand.
FW-6: Demand management initiatives	Forecasts of the impact of cost-effective and feasible demand management initiatives should be integrated into water demand forecasts.
FW-7: Demand under climate change	Water use will increase under projected hotter and drier climate conditions and decrease under projected cooler and wetter climate conditions.
FW-8: Future range of demands	Where there is significant uncertainty in demand projections over the planning horizon, water service providers should incorporate multiple demand projections into their planning process.

Discussion of principles:

A solid foundation: A good understanding of current water use is essential for projecting future water use, as discussed previously in Section 4.1.

Future range of population: Population projections are often provided to urban water resource planners for consistency with whole-of-government planning. History suggests that population projections are reasonably accurate, but that accuracy can be much lower for smaller population centres and can deteriorate significantly as the forecast period lengthens (Wilson and Rowe, 2011; Wilson, 2012). Factors that can affect population projections include:

- Net local, interstate, and overseas migration, as was particularly evident during the covid-19 pandemic when net overseas migration halted abruptly, with some demographers projecting a reduction in population growth in the decades to come as a result of that period with no net overseas migration (Charles-Edwards et al., 2021).
- Natural births and deaths, and the demographic assumptions around those.
- Other factors, such as work opportunities. For example, the future plans of large employers (existing or new) in small towns or cities can affect the future population.

Just as a water service provider might consider alternative climate change projections, if future population is uncertain, and the consequences of that uncertainty on supply system performance are potentially high, then the water service provider should also consider alternative demand projections. This may involve liaising with demographers or local government town planners to better understand these uncertainties. Not all projections need be explored to the same level of effort, but the implications of plausible alternative projections should be communicated to and understood by decision makers.

Dwelling projections can provide an alternative picture of potential future water use in addition to population projections. Where population and dwelling projections are quite different over the planning horizon, this can be a prompt to consider how these differences could manifest as changes in water use.

Per capita water use change: Per capita (or per connection) residential water use can change over the planning horizon, particularly for new residential developments with access to non-drinking water sources (recycled water, rainwater tanks, etc.), and different housing density. End use demand models, preferably informed by detailed customer meter data or end-use surveys, can assist with projecting changes in per capita residential water use. Demographic changes over time can also influence per connection water use, if the number of occupants per household changes or if the proportions of detached and attached dwellings or the size of detached dwelling lots changes.

Non-drinking water demand: Projecting both drinking water and non-drinking water demands allows water service providers to more readily seize opportunities for drinking water supply substitution using fit-for-purpose non-drinking water sources. This can be supported by integrated water management modelling at a household or neighbourhood scale.

Demand components: Demand components for specific user types can be separately projected if those components represent a significant proportion of total water demand and/or they are expected to change at a much different rate than total water demand.

Forecasting demand in tourist towns: Towns or cities with a substantial seasonal tourist population may need to consider the potential for changes in water demand (as a proportion of total demand) from those visitors over the planning horizon. The population in some smaller towns can swell to many times the permanent population over peak holiday periods, increasing water use seasonally. New major cultural events or facilities can also draw more visitors to a region. Census information in Australia is collected in August, when visitor numbers are low, which means that visitor numbers and their change over time often need to be obtained from other sources, such as tourism industry surveys. Census information in New Zealand is collected in March. If the proportion of total water demand used by tourists is expected to change over time, specific additional data collection on the number of visitors, seasonally and from year to year, and the drivers for those visits, may be required. Once the drivers for visits are more thoroughly understood, a projection for how the number of those visits might change over the planning horizon can be prepared. For example, in a hotter, drier climate, there might be fewer visits to some ski resort towns, and more visits to seaside towns, disproportionally affecting water use by visitors beyond what would otherwise be expected.

Forecasting major industrial or rural demand: Towns or cities with a relatively high proportion of water use by major industrial or rural customers can have their supply system performance heavily influenced by that demand. Businesses often plan on a much shorter planning horizon (typically not more than 12 months) than water service providers. However, engagement by the water service provider with those businesses can help to better understand their potential future water needs. This could include any plans for drinking water demand substitution for industrial uses.

Forecasting non-revenue water: Non-revenue water can include losses through water treatment plants, through the supply network, and from uncovered storages. Each of these can change over time, particularly as assets age and when new infrastructure comes online. It also includes water for firefighting. Maintaining low levels of non-revenue water into the future is influenced by the ability to maintain water supply and distribution assets in good condition. This in turn can be influenced by the resources made available to service and renew these assets.

Demand management initiatives: The evaluation of demand management options can include retrofit and rebate, community education, enhanced water system leak detection and customer water audits. The magnitude of demand reduction to expect can be informed by past demand management programs and end-use demand modelling.

Demand under climate change: Water use typically increases under hotter, drier conditions. Having a climate dependent water demand model will allow the impact of projected climate change on demand to be assessed. This can include residential water use, such as for gardens, and municipal water use (e.g. for parks and gardens), but it may also extend to some industrial water use (e.g. for evaporative cooling).

Future range of demands: Where there is significant uncertainty in demand projections over the planning horizon, water service providers should incorporate multiple demand projections into their planning process. These could include a high/medium/low or high/low demand scenario, where these represent a combination of the above influencing factors. Not all projections need be explored to the same level of effort. However, the implications of plausible alternative projections should be communicated to and understood by decision makers, with an example range of projections from a water plan in Figure 11.

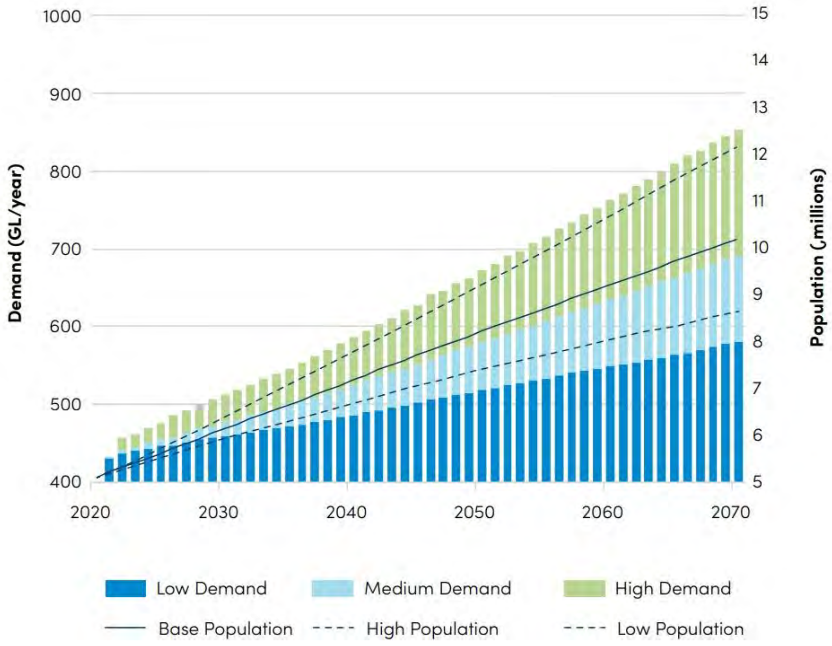


Figure 11 An example consideration of alternative population and demand projections in urban water planning (Greater Western Water et al., 2022).

The shorter the assessment time step, the less likely that changes in demand will affect urban water resource planning decisions, and the more likely that these will be related to asset planning. However, for some supply systems, changes in peak demand on shorter time steps can be important for decision making. An example would be for supply systems sourced solely from groundwater with little appreciable above-ground storage. In these supply systems, peak daily demands relative to daily bore production limits (as limited by legal entitlements to the water resource) can be critical to understanding supply system performance.

6.2 Climate change impact assessment

What is it? Climate change impact assessment involves assessing historical changes in climate and water availability and estimating the potential impacts of projected global greenhouse gas concentrations on climate, demand, and water availability over the coming decades. The following discussion does not include impacts of water service provider activities on climate change (e.g. greenhouse gas emissions from pumping water). It also does not include the impacts of climate change on water service provider assets (e.g. increased bushfire risks, increased dam sedimentation risks, changes in the risk of pipeline breakages, increased heat stress for staff, etc.).

Why is it relevant to urban water resources planning? Projected climate change is, for many regions of Australia and New Zealand, the largest threat to water availability over the coming decades. Whilst a warmer climate is certain over the coming decades, climate change projections for rainfall remain very uncertain. As a result, estimates of future water availability from climate dependent water sources are also very uncertain. Relevant principles are listed in Table 26 and discussed below.

Table 26 Water resource planning principles for climate change impact assessment

Title	Principle
CC-1: Historical climate change	The world's climate has already changed. Any climate baseline should consider the extent to which data within that baseline is stationary with respect to climate change.
CC-2: Abrupt climate change	The nature of climate change can be both gradual and abrupt. Robust options and adaptive planning increase in importance in the event of abrupt climate change.
CC-3: Bias correction and downscaling	Raw global climate model outputs are rarely application-ready for urban water resource planning without bias correction and downscaling.
CC-4: Level of confidence in climate model outputs	Just because a climate model output is available, particularly at fine temporal and spatial scales, does not mean it should be used with high confidence for all applications.
CC-5: Avoiding low confidence projections	Consideration can be given to urban water resources planning techniques that concentrate on stress testing and sensitivity testing, or which utilise relationships between different climate variables, rather than relying upon projections of low confidence.

CC-6: Earlier IPCC projections	If global climate projections are required for a given application, using global climate model projections from earlier IPCC Assessment Reports is better than not using any global climate model projections at all.
CC-7: Equally likely projections	At the current time, the projections from all global climate models included in the IPCC's latest Assessment Report are equally plausible, with no single global climate model more likely than any other.
CC-8: Emissions scenarios	Where the use of a specific emissions scenario has not been directed by government in your jurisdiction, up-to-date peer-reviewed research papers on likely emissions trajectories can help inform the selection of suitable emissions scenario(s).
CC-9: Near-term rainfall projections	Future rainfall projections for different emissions scenarios are similar up to 2030-2040, so the selection of emissions scenario up to 2030-2040 has little bearing on water resource planning outcomes.

Discussion of principles:

Historical climate change: Recorded historical climate and water availability data has a climate change signal embedded within it. The decades since the mid-1970s, for example, are notably warmer than conditions in the early and mid-20th century. Where climate and water availability data exhibits trends or step changes, it may need to be de-trended or truncated prior to its adoption as a baseline dataset. This is reflected in the use of relatively short (typically 20-30 year) climate reference periods by the IPCC and meteorological agencies around the world.

Abrupt climate change: Climate change projections are often visualised as a smooth trajectory. Whilst increases in global greenhouse gas concentrations over time have been smooth, increases in global air temperature have been characterised by periods of rapid warming, followed by periods of much more gradual warming or no warming. Changes in rainfall, runoff, the relationship between annual rainfall and runoff, and the relationship between air temperature and annual rainfall can all manifest as step changes (e.g. Jones, 2012; Jones and Ricketts, 2017). An example of this are the changes in runoff into Perth's water supply reservoirs since the mid-1970s, which were characterised by step reductions. The possibility of abrupt climate change increases the importance of adaptive planning, because such abrupt changes can occur at any time with little warning.

Bias correction and downscaling: Bias correction involves correcting climate models for bias relative to local historical observations. Downscaling involves taking global climate model outputs and making them relevant at a local scale that is typically smaller than the model grid sizes used in the global climate models. Some downscaling approaches also involve bias correction. Downscaling techniques include various statistical methods, or the use of regional climate models. Regional climate models, which cover a portion of the globe at a much finer resolution than global climate models, can however also introduce their own model biases and may also need to be bias-corrected. Statistical methods can be more robust, but can inhibit the ability to detect changes in drought duration if the downscaling method assumes that future climate has similar properties (e.g. number of rain days) to the observed historical climate.

Level of confidence in climate model outputs: Global climate models are a key tool for assessing the impacts of climate change on water resources. However the level of confidence is different for different climate model outputs. For example, global climate models project warmer future climate conditions with high confidence. Similarly sea level rise, which can result in seawater intrusion into groundwater bores sourcing water from coastal aquifers, is projected with high confidence. The level of confidence is slightly lower for projected changes in evaporation, and lower again for rainfall. The confidence of outputs at finer temporal scales (e.g. daily, seasonal outputs) is lower than at coarser temporal scales (e.g. average annual changes over 20-year periods).

Changes to climate variability under historic and projected anthropogenic climate change are less well understood than average annual changes, but are expected to include increases in rainfall intensity (as has been observed historically in Guerreiro et al., 2018). In many locations across Australia and New Zealand, it is unclear whether there will be changes to the frequency, severity, and duration of drought events. An example that was identified in south-eastern Australia from the CMIP5 modelling was that none of the global climate models in that modelling suite were able to replicate an extreme drought duration at any time in the 21st century that was as long as that observed during the Millennium Drought (~1998-2009) (Hope et al., 2015). This suggests a low level of confidence when trying to infer projected changes in extreme drought conditions from those models.

Regional climate models can provide finer spatial resolution of projected climate changes. The level of confidence associated with those models will depend upon not only the certainty of the input global climate model outputs, but also the regional climate model performance for the parameter of interest.

Water service provider understanding of these uncertainties can be improved by engagement with climate scientists.

Avoiding low confidence projections: Where the level of confidence of a parameter under projected climate change is low, consideration can be given to urban water resources planning techniques that concentrate on stress testing and sensitivity testing, rather than relying upon projections.

Global climate models generate projected air temperature with a much higher level of confidence than for other climate variables, with additional uncertainty introduced during downscaling and when converting climate change into changes in water availability. Kiem et al. (2020) and WREMA (2020b) proposed an alternative assessment approach, which uses historical relationships between annual accumulated daily maximum temperature and streamflow. This relationship is then applied to projected changes in air temperature from global climate models, to estimate projected changes in runoff into a supply system without the need for bias correction, downscaling, or rainfall-runoff modelling. The approach is attractive because of its simplicity, taking advantage of what global climate models do best, and avoiding the uncertainties in areas where the confidence in global climate model outputs is much lower. The suitability of this approach however depends upon the strength of the correlation between historical temperature trends and historical rainfall or streamflow trends.

In examples cited in the literature to date, the relationship between these two variables has significant scatter, and should be critically reviewed on a case by case basis prior to adoption.

Earlier IPCC projections: The Intergovernmental Panel on Climate Change (IPCC) produced an update to its climate change assessment report in 2007 (the 4th Assessment Report), 2013 (the 5th Assessment Report), and 2023 (6th Assessment Report). The global climate modelling from the world's climate researchers that underpins these reports is referred to as the Coupled Model Intercomparison Project (CMIP) as CMIP4, CMIP5, and CMIP6 respectively. Further updates to the latest projections are expected over coming decades. The time required to bias-correct and downscale the CMIP modelling results, often up to several years, means that there is often a several year lag between the IPCC publishing its Assessment Report and locally relevant projections being made available by researchers and government agencies. Whilst it is always best to use the most recent CMIP projections, in the context of high climate change uncertainties, using earlier projections is better than not using any projections at all. This is because the incremental differences between projections are small relative to the uncertainty in the projections themselves. Whilst newer models provide a better representation of many aspects of climate processes and conditions, the outcomes from the suite of available global climate models are still characterised by high output uncertainty, particularly for rainfall.

Equally likely projections: At the current time, the projections from all global climate models included in the IPCC's latest Assessment Report are equally plausible, with no single global climate model more likely than any other. This means that, at the current time, for a given emissions scenario, the driest climate change projections are no more or less likely to eventuate than the wettest climate change projections. Being cognisant of a wide range of projections (from driest to wettest) will better inform decision making in the face of an uncertain climate future, rather than relying exclusively upon a single global climate model projection (e.g. using the median projection only and ignoring all wetter and drier possibilities). Selecting one or more representative scenarios from the suite of available projections, for the purposes of scenario planning to support decision making, is discussed further in Section 7.2.

For some past climate change downscaling activities, some of the available global climate models have been excluded for regional applications (i.e. at a national or State scale). This should only be done where it can be demonstrated that those models performed poorly in replicating climate indicators that are very important for replicating local climate conditions.

Emissions scenarios: The language around emissions scenarios has changed over time. In the 5th Assessment Report, they were referred to as representative concentration pathways (RCPs), whilst in the 6th Assessment Report these RCPs are assigned to Shared Socio-Economic Pathways (SSPs). SSPs broadly describe the social and economic narrative associated with climate change. Whilst the RCPs are typically referred to as emissions scenarios, the modelling assumptions associated with each RCP (or SSP) include various other elements beyond emissions. These include assumed greenhouse gas mitigation measures such as carbon sequestration from the atmosphere.

Various emissions scenarios are generated by the IPCC. For the latest (6th) Assessment Report, these range from SSP1-1.9, which is described as a "very low" greenhouse gas emissions scenario, to SSP5-8.5, which is described as a “very high” greenhouse gas emissions scenario that is equivalent to the 5th Assessment Report’s RCP8.5 emissions scenario. As recognised by the IPCC, these scenarios “are used to explore future emissions […] and are based on a range of assumptions [… and] do not cover all possible futures” (IPCC, 2023). That is, there remains a possibility that the world’s future climate conditions lie outside of the range of projections presented by the IPCC. This could occur, for example, due to complex climate feedback loops or future technology advances that are not reflected in either the global climate models or the emissions scenarios. With successive updates to IPCC reports, these emissions scenarios may change in the future.

Peer reviewed research papers can provide some insights into likely emissions trajectories. These have been generated after each successive global climate conference by the world’s governments. For example, Hausfather et al. (2022) identified the actions and commitments from the world’s governments to mitigate greenhouse gas emissions following the most recent global conference on climate change (COP26) in 2021. This was compared to those assumed under the various shared socio-economic pathways modelled for the IPCC by research organisations around the world. The findings from that study provided broad likelihoods of different emissions scenarios, if current greenhouse gas mitigation commitments were to be adhered to. Similarly, the United Nations Environment Program’s Production Gap reports (e.g. SEI et al., 2023) monitor the gap between commitments to reduce greenhouse gas emissions (i.e. pledges and stated policies) and the actual plans and projections by governments (i.e. what is forecast to actually happen, which does not always align with pledges and policies). There may also be practical limitations when selecting an emissions scenario, such as the availability of suitable downscaled and bias-corrected climate model outputs in your local area for any given emissions scenario.

Planning techniques such as decision scaling (discussed further in Section 7.2), avoid the need to choose any single emissions scenario.

Lower emissions scenarios can sometimes generate drier outcomes than higher emissions scenarios, depending on the supply system location. This can particularly be the case in the near-term when climate model uncertainty (i.e. how complex physical processes are represented in the models) is generally a greater influence on climate model outputs than the input emissions scenario, as discussed below.

Figure 12 Temperature for SSP-based scenarios over the 21st century (IPCC, 2023)

Near-term rainfall projections: Climate change projections are comparatively similar up to the years 2030-2040 (see Figure 12). Climate model uncertainty, particularly for rainfall, is much greater than the uncertainty due to input greenhouse gas emissions over this time frame. This means that all emissions scenarios will generate similar changes in temperature, evaporation, and rainfall up to around the years 2030-2040, with deviation for the different emissions scenarios typically only occurring after the mid-21st century.

Future research and investigations:

Table 27 Future research and investigation to support climate change impact assessment

Research and investigation area R9: Drought duration under projected climate change. Continue research into our understanding of how the characteristics of extreme drought may or may not change under projected climate change, as this is currently poorly understood.

6.3 Risks for shared water resources including interception activities

What is it? Water use activities, upstream of a water service provider's water supply offtake points, that can affect how much water is available at the offtake point. It can include land use change, logging, plantations, and catchment farm dams, as well as changes in licensed and unlicensed water use in surface water and groundwater. It can also include potential future regulatory changes to provide water for other water uses, such as the environment and Traditional Owners / Mana whenua. Changes in water use by vegetation after bushfires is covered separately in Section 6.4.

Why is it relevant to urban water resources planning? Water sources are often shared. Whilst water service providers have legal access to water, sometimes that access can be reduced because of water use by others. If that water use by others changes over time, it can represent either a threat or benefit to the water service provider's water availability. Relevant principles are listed in Table 28 and discussed below.

Table 28 Water resource planning principle for risks to shared water resources

Title	Principle
SW-1: Risks	Shared water resources can be subject to risks outside of a water service provider's control.

Discussion of principle:

If other water uses represent a negligible component of a water service provider's water resources, or if they are known to be static over time, then they will represent a negligible threat to a water service provider's future water resources. Threats can be identified, assessed, estimated, planned for, and monitored, as shown in Figure 13. Identification of potential threats can involve engaging with the rural licensing authority, and the use of aerial photographs, remote sensing, and spatial mapping of the full extent of the supply source (noting that it may not be practical to do so for very large catchments). Specific tools or ready reckoners have been developed in some jurisdictions to assess the impact of catchment farm dams. There may be opportunities to share the responsibility for estimating and monitoring these threats with government or other water users, particularly where they have the potential to influence water availability to other water users as well.

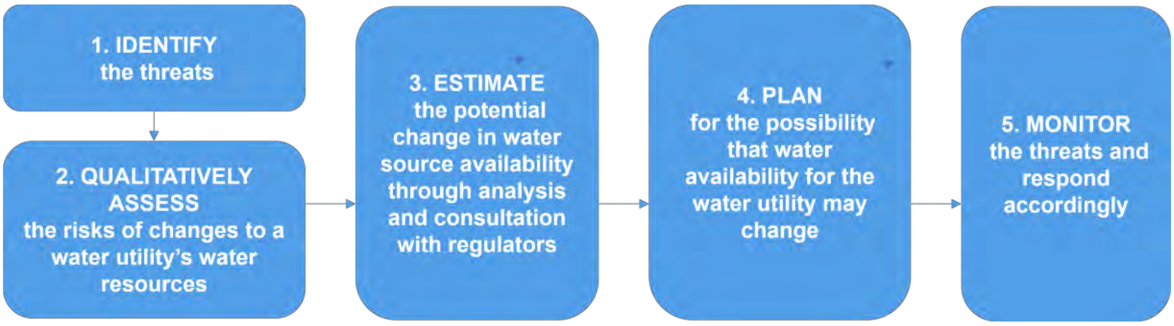


Figure 13 Assessing and responding to threats to shared water resources

6.4 Bushfire impact

What is it? The effect of forest regrowth after past bushfires on water resources and changes to the level of risk for bushfires under projected climate change. Unlike other forest management activities (plantations, logging, controlled burns), bushfires can occur over a large scale, potentially affecting all of a water service provider's water supply catchment or groundwater recharge areas.

Why is it relevant to urban water resources planning? During a bushfire event, bushfires can damage water resource infrastructure, reduce catchment water quality, and result in temporary spikes in water use as people try to protect their homes using water. In the days, weeks and sometimes months following a major bushfire, water use can drop dramatically if homes have been damaged. Water use can also drop if the water quality of surface water supply sources has been compromised due to ash, sediment and debris entering the water course. Over subsequent years and decades, runoff and recharge from bushfire affected catchments can increase or decrease in response to changes in forest age, density, and species composition.

Relevant principles are listed in Table 29 and discussed below.

Table 29 Water resource planning principle for bushfires

Title	Principle
BF-1: The Kuczera curve	The Kuczera curve of bushfire impact on streamflow was unique to a specific forest type (Mountain Ash) after a specific bushfire event with specific pre-fire forest conditions. This curve is not universally applicable. In other forest types and fire events, in the years and decades after fire, there may be a similar reduction in streamflow, or a lesser reduction, no change, or even an increase in runoff.

Discussion of principle:

The water resource risks from past bushfires will be influenced by (i) the extent of vegetation cover in the upstream catchment or groundwater recharge zone, (ii) the forest composition before the fire, (iii) the time since the fire, and (iv) the burn severity (i.e. whether the fire killed all of the trees, just killed all of the undergrowth, or just scorched the canopy). The most widely known impact of bushfires on surface water resources is the "Kuczera curve". This curve is derived from empirical analysis of behaviour in Mountain Ash forests after the 1939 bushfires in south-east Australia (Kuczera, 1987). More recent analysis of bushfires from other locations suggests that the Kuczera curve is accurate, but only for the event and locations from which it was derived (Lane et al., 2023). Where available, paired catchments with burnt and unburnt areas can provide local insights about the extent to which water generated from the catchment is changing.

Under projected hotter and drier conditions, the risk of future bushfires would be expected to increase, as well as the fire intensity and the severity of the burn.

6.5 Changes in runoff and recharge during and after extended drought

What is it? During and after the Millennium Drought (~1998-2009) in south-east Australia, it was observed that some surface water catchments generated less annual runoff for the same given input annual rainfall (e.g. Saft et al., 2015). This research suggested the potential for a catchment to shift state from a higher water yielding catchment to a lower water yielding catchment in response to extended drought, assuming the same input rainfall conditions. Similar shifts in rainfall-runoff response have also been observed in south-west Western Australia (e.g. Hughes and Vaze, 2015).

Why is it relevant to urban water resources planning? If this shift in runoff occurs, it can result in a water service provider having less water available to harvest during (and after) an extended drought, than was available leading into the drought. This indicates that some catchments are less reliable during and after extended drought than they are at other times, which can affect both water harvesting during drought and the speed of recovery (if any) after drought. Relevant principles are listed in Table 30 and discussed below.

Table 30 Water resource planning principle for changes in runoff and recharge during and after extended drought

Title	Principle
RR-1: Extended drought	Just because a catchment has generated a certain water yield historically, does not mean that the same yield (for a given input rainfall) will always be available during and after an extended drought.

Discussion of principle:

The reasons for this observed shift are still a matter of conjecture, with various potential explanations put forward for ongoing research. For water service providers it is important to be aware of the risk, monitor it, and have a plan in place for the possibility of such a shift.

A free tool was developed by Melbourne and Monash Universities to detect phase changes in annual rainfall-runoff response using Hidden-Markov models. This tool can be used (albeit with some understanding of the theory behind the model) to assess if a catchment has shifted state from a higher to a lower yielding catchment, vice versa, or not at all. See the supplementary materials in Peterson et al. (2021) for access to this tool.

Future research and investigations:

Table 31 Future research and investigation to support changes in runoff and recharge during and after extended drought

Research and investigation area R10: Changes in rainfall-runoff: Continue research into the potential causes of the observed shift in rainfall-runoff in some urban water supply catchments during and after extended drought, including the variance in time frames to return to a pre-drought state, and further development and case studies to improve the uptake of the tool for water service providers to monitor this risk.

7. DECISION MAKING

7.1 Future uncertainty, robustness, and resilience

What is it? Future uncertainty is the inability to precisely know what input conditions will eventuate for a supply system over the planning horizon. Robustness is the ability of a supply source or supply system to withstand different input conditions without unacceptable deterioration in performance. For example, a supply system would be considered robust in the face of drought if it can maintain performance through the use of climate independent water sources, contingency supply measures, voluntary demand reduction, etc. The adaptability of a supply system can contribute to its robustness.

Why is it relevant to urban water resources planning? Robust supply systems will be more resilient to uncertain future conditions.

Table 32 Water resource planning principle to achieve robustness

Title	Principle
UN-1: Importance of robustness	Supply systems that are robust to future uncertainties will be more resilient, with lower regret for planning actions. Adaptability can contribute to robustness.
UN-2: Supply diversity increases resilience	Having access to different types of water sources reduces the risks of failure of any one water source.

Discussion of principles:

Importance of robustness: Under an uncertain future, the robustness of performance metrics under many scenarios can be just as important or more important than a supply system's performance under any single scenario. A supply system's adaptability can contribute to its robustness.

Measures of robustness can include identifying the least-worst outcome (i.e. the best performing option in the scenario that generates the option’s worst outcome), interpolating between the best outcome and the least-worst outcome (i.e. an option that performs moderately well in the scenario where it performs the best, and moderately well in the scenario where is performs the worst), equally weighted futures (i.e. an option that on average performs best across all scenarios), or selecting the strategy that has the highest utility in the most futures (i.e. an option that most frequently performs well across all scenarios) (Marchau et al., 2009).

Adaptability is the ability of a supply system to be modified under changing conditions to better meet supply system performance objectives. Strategies to increase adaptability could include having temporarily deployable assets on hand (e.g. portable package desalination plants, or access to water market allocations), infrastructure whose construction and commissioning can be staged, and infrastructure that can be readily decommissioned or deployed elsewhere if it is not needed.

Supply diversity increases resilience: Having access to diverse water sources reduces the risks of failure of any one water source. For example, a climate independent source of water can help to maintain supply if a bushfire temporarily reduces water quality from surface water sources. In south-east Queensland, supply from the Gold Coast Desalination Plant has been strategically used to increase supply during extended periods of maintenance of other assets. This included when a major water treatment plant was offline for upgrade works, thereby substantially reducing the risks of this maintenance work (Queensland Minister for Natural Resources, Mines and Energy, 2020).

7.2 Planning approaches to support decision-making

What is it? According to Marchau et al. (2019), deep uncertainty occurs because the physical, social, economic, and political systems in which planning takes place are not sufficiently well known to fully and accurately quantify and assign probabilities to that uncertainty. For questions of deep uncertainty, additional data or information cannot be gathered at the current time that would reduce that uncertainty.

Why is it relevant to urban water resources planning? For most urban water supply systems, urban water resources planning occurs in an environment of deep uncertainty. Specifically, climate change, population projections, and regulatory change are areas with the greatest influence on urban water resource planning for most supply systems, and all are an area of deep uncertainty.

Relevant principles are listed in Table 33 and discussed below.

Table 33 Water resource planning principles for planning approaches to support decision-making

Title	Principle
PA-1: Scenario planning for most applications	Scenario planning is well suited for most applications and is usually the easiest approach to develop and communicate.
PA-2: Representative scenarios	Where there are many input scenarios, but few response options, representative scenarios (sometimes called narratives) can be used to reduce the number of input scenarios. This allows scenario planning approaches to still be used.
PA-3: When to use other approaches	Approaches other than scenario planning can be more useful for decision making when: (i) There are many input scenarios that are irreducible; and/or (ii) There are many response options to consider; and/or (iii) The available input scenarios do not adequately represent potential risks; or (iv) There is insufficient information to make an informed decision.
PA-4: Stress testing	Stress testing can be used for supply systems where available input scenarios do not adequately represent potential changes to threats and opportunities.
PA-5: Investing to reduce uncertainty	Investment to reduce input uncertainty can improve subsequent decision-making.

PA6: Adaptive planning and management	Adaptive planning and management reduces the regret associated with sub-optimal decisions due to future uncertainty.
PA7: Swapping approaches	Using more than one planning approach to inform decision making is not cost effective, unless the current planning approach is unable to adequately inform a decision and the consequences of a poor decision (i.e. its regret) are potentially very high.

Discussion of principles:

Scenario planning for most applications: The most common water resource planning approach adopted in Australia and New Zealand is scenario planning in combination with some form of adaptive planning and/or adaptive management. This involves:

i. Having a basic understanding of supply system risks and opportunities, which may be informed by historical or modelled supply system behaviour;
ii. Defining one or more scenarios related to those risks over a planning horizon;
iii. Identifying actions that best meet the supply system performance objectives for a preferred scenario;
iv. Considering what-if scenarios outside of the preferred scenario to test the robustness of those actions and modifying them accordingly; and
v. Designing and implementing a monitoring regime to track behaviour against defined triggers for implementing alternative actions as part of adaptive planning.

For supply systems where supply system risks are low, a scenario planning approach with adaptive planning elements, as described above, is likely to be the easiest to develop and communicate to enable effective decision making.

For items (iii) and (iv) above, the assessment of options is typically undertaken using cost-benefit analysis (if performance metrics can all be expressed in or converted to dollar terms), multi-criteria analysis (where they cannot), or a pareto-front of one or more of those performance metrics. Pareto-front optimisation is explained later in this section. Decision scaling and pareto-front optimisation are considered “scenario neutral” approaches because they do not rely on any single scenario for decision making. Other planning approaches exist in the academic literature (see Marchau et al., 2019), however these have gained little traction to date in water resource planning applications. An example of this is the real options approach (Borinson et al., 2008), which is used in finance to hedge investment decisions. It has not been adopted in water resources because it depends upon assigning a likelihood to all scenarios, when in many cases, no such likelihood can reliably be assigned.

Having an initial understanding of risks and opportunities helps to frame the problem and inform the selection of an appropriate planning approach. This understanding can come from lessons learnt from historical operation and performance, modelling of current supply system performance, or through more formal sensitivity testing (i.e. if we change an input variable or a characteristic of that variable by say 10%, 20%, etc., how sensitive are the performance metrics to that change?).

Representative scenarios: Where the number of potential scenarios is high, it is often difficult to both model and communicate the nature and outcomes of all of these scenarios to decision-makers. One strategy for addressing this is to characterise the range of potential scenarios using representative scenarios. A practical example of this is the use of a 10th, 50th, and 90th percentile climate change projection in the Victorian climate change guidance (DELWP, 2020), whereby dozens of alternative climate change projections are condensed to three representative scenarios. Where representative scenarios combine different risks, care must be taken to ensure that they remain plausible and reasonably internally consistent. When representative scenarios become very low likelihood, this should be conveyed to decision makers, with any implausible scenarios removed.

With respect to different climate risks, in recent guidance developed by the Western Australian government (DEWR, 2023), a storylines approach is recommended. This results in physically self-consistent plausible pathways, which is not always possible when selecting different climate model outputs statistically from different climate models. The storylines approach may not always reduce to a subset of representative scenarios, because as many scenarios as needed are used to tell the story of projected climate change and its impacts on the supply system. This may include using all available climate models. However, the option is available with this approach to reduce the number of scenarios where different climate models are telling a similar story for the water supply system of interest.

Where the implications of individual scenarios are different, they need not all be investigated to the same level of rigour, provided that the performance associated with all scenarios is broadly understood and retained in reporting for decision makers. An urban water resources plan should be capable of responding to higher risk scenario(s), and more effort can be spent on planning for higher risk scenario(s) to ensure that this is the case. This includes investing in readiness for higher risk scenario(s). However, by also being aware of lower risk scenarios, elements of adaptability can more readily be embedded into the urban water resources plan if those lower risk scenarios were to eventuate. By gaining awareness of all plausible scenarios, a water service provider’s risk appetite can also more transparently be discussed.

When to use other approaches: Dewar (2006), as reported in Marchau et al. (2019), concluded that scenario planning can effectively be applied when uncertainty was either well-characterised or deep, but was less preferable when system complexity was high and when there were many implementation options available. Defining and communicating scenarios, and assessing potential actions under those scenarios, becomes more difficult under these circumstances. This is when other planning approaches can potentially be considered, as represented visually in Figure 14 and outlined below.

Approaches other than scenario planning can potentially be more useful for decision making when:

i. There are many input scenarios that are irreducible; and/or
ii. There are many response options to consider; and/or
iii. The available input scenarios do not adequately represent potential risks; or
iv. There is insufficient information to make an informed decision.

Choosing only one approach will require less effort in technical analysis and communication, and will avoid any potential conflicts (if they were to arise) due to different assessment methods generating different outcomes. However, in some cases different approaches can be complementary.

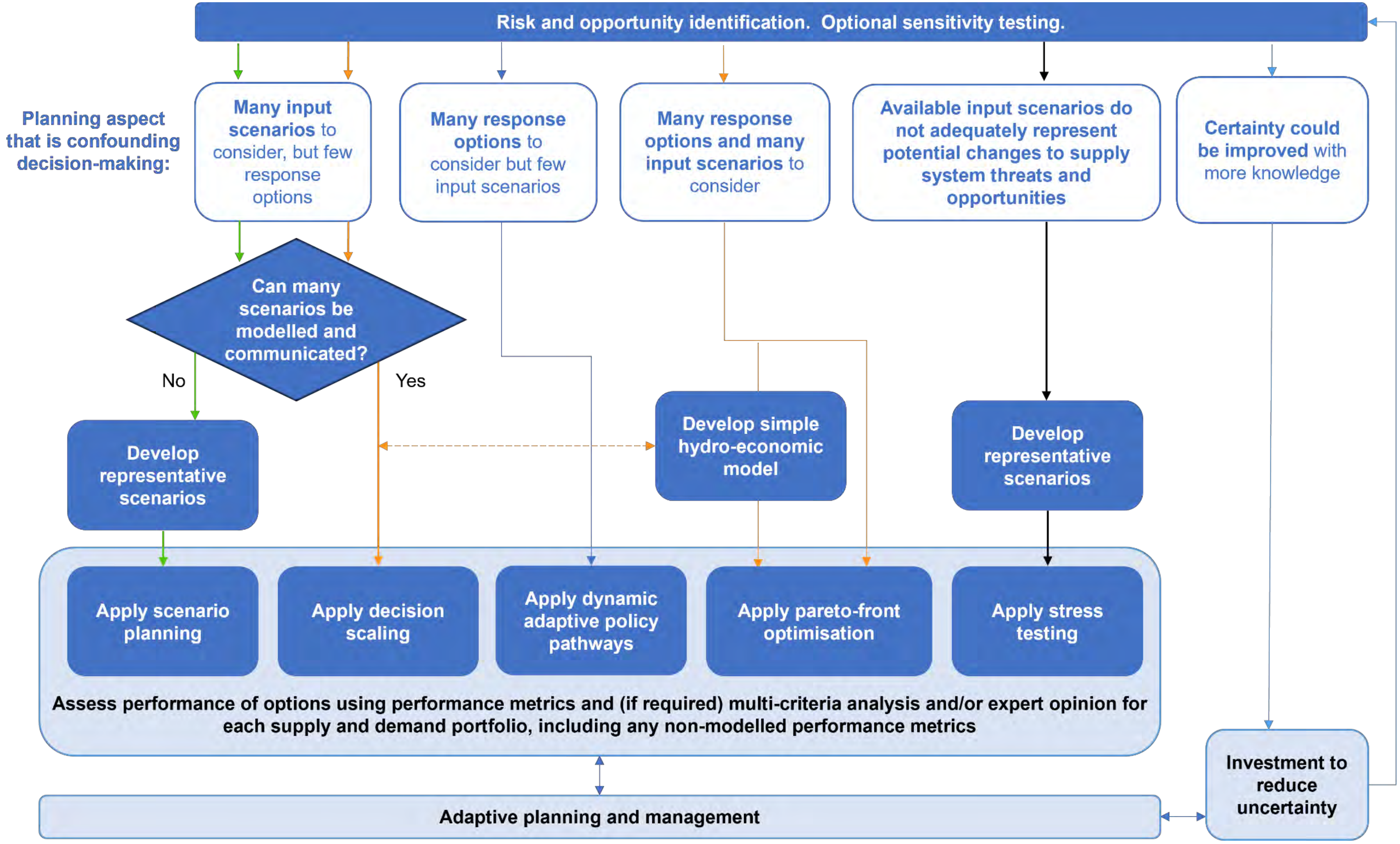


Figure 14 Planning approaches for managing future uncertainty when decision making using scenario planning is being confounded

Stress testing: Stress testing involves identifying the conditions under which a supply system would no longer meet its performance objectives (i.e. the conditions which would cause stress). Stress testing differs subtly from sensitivity testing in that rather than testing a consistent, discretised change in inputs (e.g. ±10%, ±20%), scenarios are developed which are considered likely to cause stress, including scenarios that breach performance objectives. These scenarios need not always be plausible, as understanding that a highly unlikely or implausible scenario is required to create stress can also be a useful modelling outcome to inform water resources planning.

Stress testing can be used for supply systems where available input scenarios do not adequately represent potential changes to threats and opportunities. An example of this would be for run-of-river supply systems with little storage capacity relative to inflows and demand. For this type of system, stress could occur due to changes in low flow duration over time frames of a few days to a few weeks. Climate change projections are, in many cases, unable to reliably identify future changes in the number of rain days, particularly at local scales. They might therefore not be able to reliably inform whether low flow conditions at a location of interest might change. Under this circumstance, it could be more informative to stress test the system, to identify by how much cease-to-flow conditions would need to change before supply system performance would be compromised. Possible response options for that scenario (which is an output of the supply system stress testing) could then be considered and assessed. The level of effort to address this potential risk would still need to be weighed up against its likelihood, which may not be known.

Stress tests can also be used for assessing how much the integrity of a supply system could be compromised (e.g. due to disasters or other supply system shocks) without compromising performance relative to objectives, as discussed further in Section 7.5.

Decision scaling: Decision scaling has potential advantages for supply systems with many input scenarios and few response options. Decision scaling is a ‘scenario neutral’ planning approach that initially makes no explicit assumptions about future conditions. Rather it involves testing the sensitivity of a supply system under a hypothetical range of climate, population growth, or other uncertainties. This is used to better understand the system’s vulnerability and robustness to changing conditions, for a given supply system configuration and operation. Once this sensitivity testing has been undertaken to generate performance metrics for a given range of input variables (e.g. for an X%, Y% and Z% change in rainfall, temperature, and/or or population), the input conditions for any assumed scenario can readily be plotted onto those sensitivity test results.

For example, rather than modelling supply system performance under projected climate change for the year 2040 under the SSP2-4.5 and SSP1-2.6 emissions scenarios (as would be done for scenario planning), the climate perturbations from those climate change projections are simply plotted onto the sensitivity test results. This illustrates how well the supply system would perform under those climate scenarios. This can be repeated for an infinite number of input climate and population growth scenarios, with each new scenario simply being a new point mapped onto the sensitivity test outcomes. Decision scaling works very well when there are lots of potential scenarios, rather than focusing of one or only a few scenarios, which has led to its appeal for climate change applications (e.g. Figure 15). See

Henley et al. (2019) for an application of decision scaling applied to an urban water supply system.

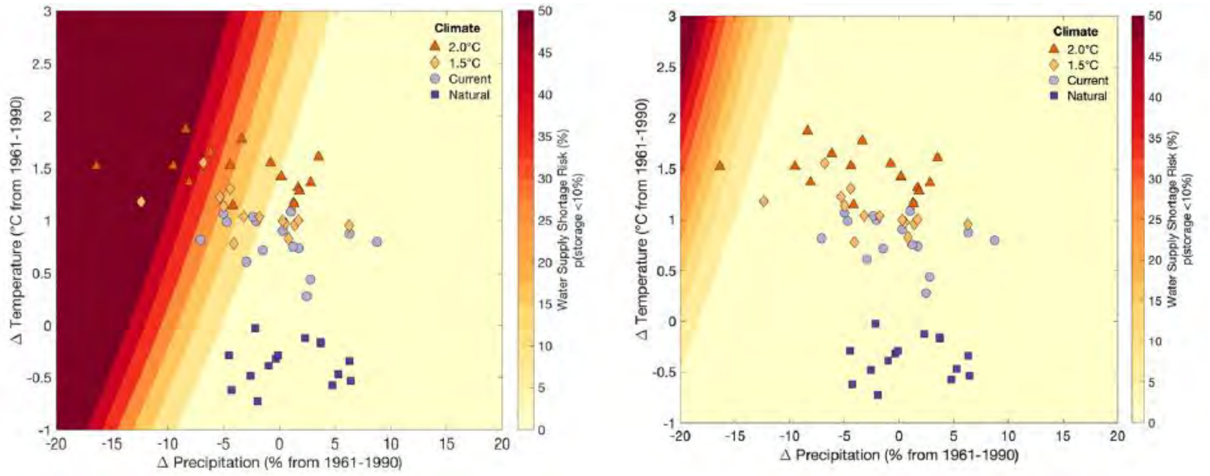


Figure 15 An example of decision scaling applied to average changes in air temperature and precipitation when assessing system performance for a supply system without (left) and with (right) a supply augmentation option (Henley et al., 2019)

It also has the advantage that:

- It allows an assessment of system performance independent of the uncertainties associated with global climate models and their downscaled outputs;
- It generates sensitivity test results that remain valid even if global climate models are subsequently updated; and
- By allowing decision-makers to see the performance outcomes of all scenarios at once, it directs decision-makers to give greater weight to system resilience and adaptability to future uncertainty, rather than its optimal performance under a limited number of scenarios.

Decision scaling however has the following disadvantages in that:

- It can significantly increase the water supply system modelling effort, particularly for perturbations of multiple variables;
- Outcomes become more complex to present and interpret when there are more than two variables being perturbed at any one time. For example, results of a sensitivity test for one performance measure for an assumed change in average annual rainfall and population, for one supply system configuration and operation, can readily be plotted in a two-dimensional space. Sensitivity testing for more than one performance measure, or for more than two variables, results in outcomes in a multi-dimensional space. This becomes much more difficult to communicate and interpret. Outcomes need to be duplicated for each supply system configuration and operation, and for each point in time over the planning horizon for which outcomes are required;
- It may, without careful consideration of the co-variance of different variables, generate unrealistic combinations of input variables, which can distract decision making; and

- It may require climate response functions or models to be created, for supply system inputs that are not modelled (e.g. where inflows are used directly, rather than climate inputs to a rainfall-runoff model).

Pareto-front optimisation: Pareto-front optimisation is a modelling technique that can be used to support decision making that is well suited to supply systems with many potential input scenarios and many potential response options. It involves modelling all of these scenarios and options, typically with a hydro-economic model, to identify a subset of solutions with high performance and low regret under the range of scenarios tested. Once the subset of more attractive solutions has been identified, other decision making techniques such as expert opinion or multi-criteria analysis are applied to select a preferred solution. Given the extensive modelling effort that is often involved, the representation of the supply system in these hydro-economic models has sometimes been simplified. Refer to Cui and Kuczera (2010) or Purves et al. (2015) for examples of pareto-front optimisation applied to urban water supply systems. In Figure 16, seven representative supply configurations were identified along the pareto-front, ranging from higher cost but lower regret options to lower cost and higher regret options. These seven configurations could then be assessed in more detail and presented to decision makers to assess their risk appetite and willingness to invest.

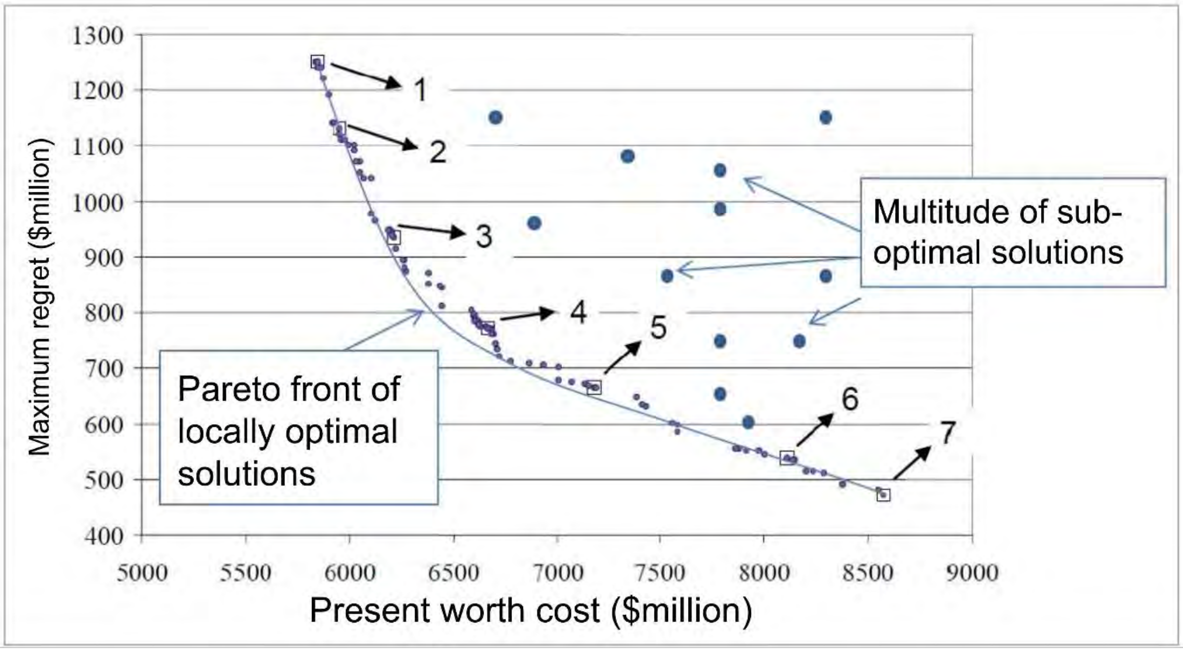


Figure 16 Example two-dimensional pareto-front (adapted from Cui and Kuczera, 2010)

Dynamic adaptive policy pathways: In the “dynamic adaptive policy pathways” approach presented by Deltares (2019), adaptation pathways are visualised (as seen in Figure 17), with each potential pathway assessed against a simple scoring system. Each pathway includes a trigger point (or transfer station), a lead time to the implementation point, and a threshold (or tipping point) for adopting an alternative pathway under changing conditions. Implicit in this approach is that designated performance objectives are maintained along each pathway. Decisions are then made by consensus, informed by the costs and benefits of each pathway. A more practical discussion of this approach for a water service provider can be found in Maynard et al. (undated).

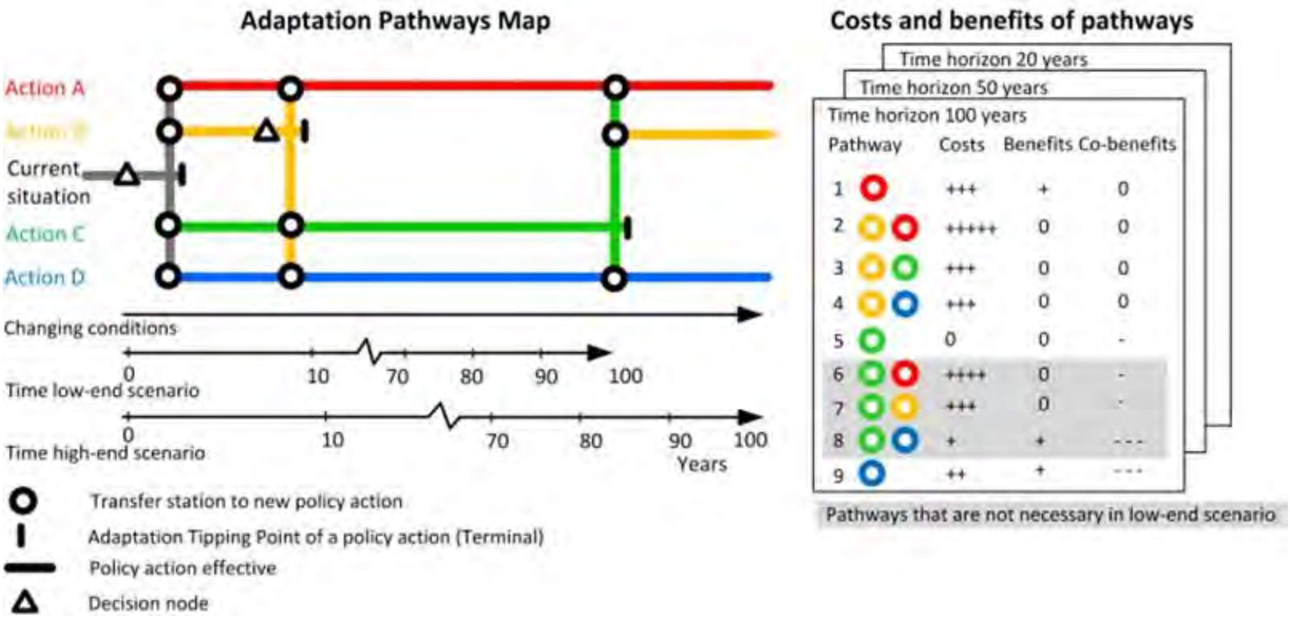


Figure 17 An example of an Adaptation Pathways Map (left) and scorecard (right) (Deltares, 2019)

Such an approach is best suited to supply systems where the options available are well understood, but their preferred sequencing is not. It also has the advantages that:

- It is visual in nature, for example highlighting option dependencies, sequencing, and the design life of options; and
- It can allow enabling actions for future pathways to be reserved (e.g. setting aside land for infrastructure that is likely to be needed in future decades under the preferred pathway).

It has the disadvantage that:

- There is limited ability to represent multiple input scenarios.

<u>Adaptive planning and management:</u> Adaptive planning and management involves establishing triggers to adjust actions in response to changing conditions. All approaches to adaptive planning and management involve defining the problem, specifying options for addressing the problem and their constraints, identifying a promising initial plan using a simple planning technique (e.g. multi-criteria analysis or the outcomes of scenario planning as described above), identifying and assessing vulnerabilities, and designing a monitoring system with triggers for action.

In the more formal adaptive management approach adopted in Kwakkel et al. (2010), actions are described as mitigating (to address likely vulnerabilities), hedging (to cater for uncertain vulnerabilities), or seizing (to take advantage of likely opportunities). Monitoring is used to trigger actions that are classified as defensive actions, corrective actions, reassessments, or capitalizing actions. In urban water resources planning, adaptive planning typically occurs in the context of drought. During drought, current or near-term projected supply system conditions can be used to trigger not only short-term contingency supply measures, but also to bring forward or defer planned actions identified in long-term water resource strategies. Adaptive planning triggers can also be related to population growth, community consultation outcomes, or regulatory approvals.

An example of adaptive planning is the preparation of an Annual Water Outlook by water service providers in Victoria (DELWP, 2021). The outlooks confirms whether any adjustment is required to actions from a water service provider's long-term water resource strategy as a result of current and forecast conditions over the next 12 months. Such a process is illustrated in Figure 18 and includes:

- A strategy that identifies actions to be implemented prior to the next strategy review (in ~5 years' time) and in the long-term (from 5-50 years). This can include specific triggers developed for option readiness (i.e. evaluating options to an extent that enables their selection), selection, and implementation, as outlined in Greater Western Water et al. (2022);
- An annual review (every year from years 1 to 5) of the supply system status and the status of potential threats to supply system performance. This can be used to trigger changes to the timing or nature of planned actions without revisiting the whole strategy; and
- An emergency response plan that identifies emergency response options in real-time for known stressors (for example, drought), as agreed during the planning process, or if conditions rapidly change such that long-term planning actions are unable to be implemented to avoid an emergency response.

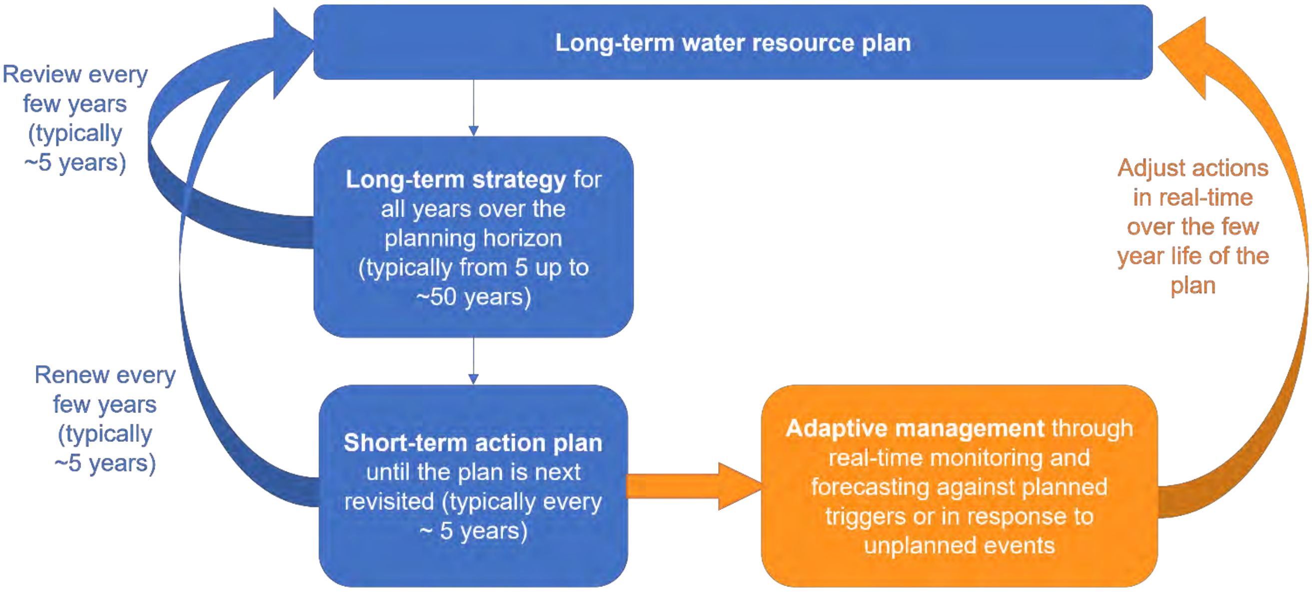


Figure 18 Adaptive management over the life of a long-term water resources plan

Investing to reduce uncertainty: Real options is a technique developed in the finance industry for the progressive investment in a portfolio of financial assets. The potential application of a real options approach to urban water resource planning was presented in a previous WSAA paper (Borinson et al., 2008). The mechanics of a formal real options approach for application in water resource planning has not successfully been implemented in Australia or New Zealand to date. This is because it relies upon being able to assign likelihoods to future scenarios, which in urban water resource planning, are usually of unknown likelihood. Nevertheless, a core concept from a real options approach is useful for urban water resources planning. This is that there can be benefits from incremental investment in multiple response options to either reduce the uncertainty associated with those options (so as to be able to make decisions with higher confidence in the future), or to reduce the lead time associated with them. If a water service provider has a fixed capital budget available to spend, it must decide where best to invest those funds. This could include investing in monitoring, community consultation, modelling, or research and development.

Swapping approaches: If the planning approach being used is unable to adequately inform decision making, then alternative approaches can be considered. This is most likely to occur when the range of potential futures is diverse, and the number and diversity of response options is high. In most cases, using more than one planning approach to inform decision making is not cost effective. However, if the consequences of a poor decision (i.e. its regret) are potentially very high, then the additional investment may be warranted. Examples of regret could involve investing in water supply infrastructure with a large capital cost that never gets used because a wetter future eventuates, or building a reservoir that never generates its intended yield because a drier future eventuates. Sometimes tackling a water resource planning problem in a different way can unlock insights that are unable to be seen using only one approach.

Future research and investigations:

The Water Research Foundation, which is a not-for-profit research foundation based in the United States, called for research proposals in 2022 into “Guidance for Adaptive and Scenario Supply Planning Approaches (RFP 5184), which may provide further insights into planning approaches.

7.3 Decision-making

What is it? Making decisions about actions to take as part of an urban water resource plan.

Why is it relevant to urban water resources planning? Decision making enables actions to be taken that are expected to best meet the supply system performance objectives over the planning horizon.

Relevant principles are listed in Table 35 and discussed below.

Table 34 Water resource planning principles for decision-making

Title	Principle
DM-1: Collaborative, informed, evidence-based decision making	Urban water resources planning decisions are best made by consensus, by people, informed but not made by algorithms, models, numbers, charts, or planning approaches. Decision making should be evidence-based and transparent.

Discussion of principle:

The previous chapter discussed planning approaches available to support decision making, informed by modelling tools that provide input to those planning approaches. Water resource planning decisions are however made by consensus, by people, not by algorithms, models, numbers, or charts. Those decisions will inevitably be influenced by emotion and sentiment, taking into account the often intangible variables that are also important for decision making. For some major projects, decision-making will also be influenced by the perceived political consequences, and the group of decision-makers may be restricted to government ministers or government leaders.

The more that these external factors can be transparently recognised, the more that a planning strategy will be defensible and embraced by all parties. Water resource planning decision making is usually by consensus amongst a group of representative stakeholders. It is typically not put to a public vote, although public opinion can heavily influence decision-making where there is community aversion to a proposed action. Not all decision makers will necessarily hold equal weight when making a decision, and some proposed actions will be more heavily influenced by regulators than water service providers.

Decision making can be aided by understanding when a decision needs to be made. That is, separating out decisions for now, relative to decisions for subsequent planning cycles. This could include actions now that mean a water service provider is in a better position to make a “decision for now” in a subsequent planning cycle.

The overall approach to decision making involves:

1. Identifying the stakeholders in the planning process, and educating them about the planning process and its importance;
2. Collaboratively defining level of service objectives for the water supply system with customers and other stakeholders;

3. Collaboratively defining other performance measures that are important to the community;
4. Identifying risks and opportunities for the supply system in relation to those objectives and performance measures;
5. Developing decision support tools to inform supply system behaviour relative to those objectives and performance measures;
6. Selecting a planning approach suitable for the level of risk that it is facing, the number of input scenarios to consider, and the number of response options available;
7. Exploring different response options and combinations of response options to develop alternative supply system configurations over time. Adjusting level of service objectives can also be considered a response option. This step involves assessing the performance of the supply system over the planning horizon under the range of input scenarios and response options available, including the robustness of the supply system to different input scenarios. This may involve combining the performance metrics (e.g. in a cost benefit analysis or multi-criteria analysis) or considering them alongside one another;
8. Narrowing the preferred response options by eliminating unacceptable or less preferred responses;
9. Developing one or more strategies from the preferred response options to meet the level of service objectives and to best meet other performance objectives. This should include adaptive planning elements to potentially switch from one strategy to another once more is known about future uncertainties. It will also involve defining in more detail the actions which need to be undertaken prior to the next planning cycle to support the implementation of those strategies;
10. Testing those strategies with customers and other stakeholders; and
11. Bringing together decision makers, who will have been informed and involved throughout the above steps, to come to a consensus decision on a preferred long-term strategy and a preferred short-term plan of action prior to the next planning cycle.

As indicated above, this is a collaborative approach, typically taking place over many months or years, with no black-box answers, and a commitment to ongoing monitoring, adjustment and (where necessary) revision of decisions as new information emerges.

7.4 Drought planning links

What is it? Establishing transparent links between short term drought planning assumptions and long-term water resources planning assumptions.

Why is it relevant to urban water resources planning? Adaptive management as part of drought planning informs and, where necessary, modifies long-term water resource planning decisions.

Relevant principles are listed in Table 35 and discussed below.

Table 35 Water resource planning principles for drought planning links

Title	Principle
DL-1: Preserving design intent over time	The design intent of operational triggers for drought should be preserved, over the whole planning horizon, in any assessment of supply system performance for long-term water resources planning.
DL-2: Consistent planning assumptions	The assumptions for drought planning and long-term water resource planning should be consistent, or transparently identified where they are deliberately different.
DL-3: Adaptive management due to drought	Adaptive management as part of drought planning informs and, where necessary, modifies long-term water resource planning decisions. Lead times for actions influence the ability to adaptively implement those actions.

Discussion of principles:

Preserving design intent over time: Implicit in the design of any operational triggers for drought response is an assumed length of time until a future condition (such as dropping to a minimum operating level in a reservoir) is reached, under an assumed level of demand. Operational triggers for drought response could include triggers for voluntary demand reduction campaigns, mandatory restrictions, or bringing online contingency supply measures. When the level of demand changes, then the operational trigger would also be expected to change, so as to preserve the design intent of the operational trigger. These operational triggers are usually linked to an assumed drought duration (whether explicitly or implicitly). Sometimes they are linked to an assumed lead time to implement contingency supply measures or long-term water resource planning options.

By way of example, an operational trigger to reduce demand could be put in place to extend the duration of supply in a 1 in 100 annual exceedance probability design drought to say 12 months. This is because (in this hypothetical example) it is estimated that it will take a minimum of 12 months to bring a planned new supply option online. If demand increases over time, for example under population growth, then the duration of supply available under that design event will reduce. If it were to reduce to say 10 or 11 months, this would result in the minimum operating level in the reservoir being reached prior to the new supply option being available to use. Therefore, in order to preserve the design intent of a 12-month lead time, the operational trigger would need to set at a higher level in storage. This would trigger the action earlier in the drought event, and more frequently on average over the long-term. In supply systems with high demand growth, the consequences of this on supply system reliability and yield over the planning horizon can be profound. However, adjusting operational triggers as part of yield or reliability of supply assessments makes water resource modelling more cumbersome. It is only suggested in supply systems where changes in demand could affect the design intent of the operational trigger.

Consistent planning assumptions: The assumptions for drought planning and long-term urban water resource planning should be consistent, or transparently identified where they are deliberately different. This would include, for example, using the same operational triggers in both planning processes, and having a level of demand, for the life of a drought plan, that is consistent with the long-term plan. There can be deliberate differences in assumptions, for example, assuming a dry year demand for drought planning, or different types of analysis might be undertaken that require different input assumptions (e.g. if undertaking stress testing of drier water availability scenarios for drought management planning only). In both cases, those assumptions should be consistent with actual system operation, unless there are clear reasons why they are different (e.g. operators having to deviate from planned water resource triggers for reasons unrelated to water resources).

A design drought is a climate (or streamflow or recharge) sequence over a given duration, which may or may not have a known likelihood, that is used to inform drought response planning. The concept of a design drought can be useful within a risk management context when assessing lead times available for drought response actions and when designing operational triggers for drought response. It can also be used to test system performance as part of stress testing from a given starting water resource position. A design drought can be based on a historical event (such as the worst drought on record), a modified historical event (to generate a sequence that is drier than the worst drought on record, such as back-to-back severe drought years or months), or a synthetic event (e.g. one or more generated from a stochastic model). If using the worst drought on record, water service providers should ensure that their plan of action considers the possibility of droughts occurring that are worse than the worst on record. If using a drought worse than the worst on record, the drier an event becomes, the lower the confidence that it will remain physically plausible. The length of the design drought should reflect the critical period for the supply system (i.e. how long it takes from the start of resource depletion to supply system failure), which will be informed by the historical and modelled supply system response to climate inputs. The critical period could range from days for run-of-river supply systems, to many years for supply systems with large storage capacity, and could change under future climate conditions or different supply system configurations. Similar to long-term planning objectives, there is no universal standard for the likelihood associated with a design drought. Rather the likelihood should reflect community and stakeholder expectations for managing risks for the particular supply system. Design droughts, by their nature, simplify the representation of potential drought events, which can be useful for planning and communication purposes. However in practice those future events will involve alternative sequencing and a severity that is different than that assumed in the design event. This can be addressed, if needed, by exploring multiple potential drought sequences.

Adaptive management due to drought: For supply systems with climate dependent water sources, but insufficient contingency supply options available during drought, the most appropriate drought response option can be (despite any demand reduction measures put in place) to implement the next planned supply system augmentation. Urban water resource planning actions scheduled on the basis of long-term reliability of supply and yield may result in a supply enhancement option being scheduled to occur in say ten years' time. However, if a severe drought were to occur in less than ten years' time, and there are no other suitable contingency supply options, then the planned response option would need to be implemented sooner. This would be triggered by a monitoring action linked to preserving the lead time associated with bringing the supply option online in time to maintain sufficient supply during the design drought.

Similarly, for supply systems with climate dependent water sources, in wetter periods the implementation of the long-term water resource planning option could be deferred if available supplies provide a lead time longer than that required to implement the option. In this case, the scheduled implementation could be pushed out from the planned ten-year time-frame to say 11 or 12 years until drier conditions return.

The planning difficulty arises when the lead time to implement the next planned augmentation option is longer than the supply time available under the design drought event, regardless of the current year's climate conditions. Under this situation, if an extreme drought event were to occur, the option would not be able to be implemented in time to assist with maintaining supply. Possible responses in this situation include:

- Improving the readiness of an option. This involves progressing the planned augmentation option so that its lead time is reduced to a duration where it could be implemented at shorter notice, sufficient to contribute supply during the design drought. This could include reserving land, obtaining regulatory approvals, or undertaking some early engineering works. An example of this was south-east Queensland's Western Corridor Scheme (Seqwater, undated), which was made ready to provide water into the drinking water supply system, but has to date only been required for non-drinking water purposes.
- Implementing the supply option. This can have cost and political consequences if conditions remain wet and the option is not needed for several years after the option is implemented.
- Revisiting both long-term planning options and drought response options to see if a less attractive option, previously dismissed, could result in a better outcome for supply system performance under these specific circumstances.
- Considering and communicating to customers a short-term reduction in level of service while the option is implemented

Berghout (2009) provides a practical example of how lead times for drought response and long-term planning actions can influence long-term water resource planning decisions.

7.5 Supply system shocks

What is it? Rapid, unplanned disruptions to the supply system that affect the ability to supply water on an ongoing basis. These can be due to events such as storms, earthquakes, tsunamis, bushfires, chemical spills, wilful damage, etc. The following discussion does not include temporary unplanned interruptions to service to individual customers or groups of customers as a result of normal operations (e.g. pipe breakages). It also does not include rapid onset droughts, which are covered separately under Section 7.4 alongside other types of droughts.

Why is it relevant to urban water resources planning? Supply system shocks can limit the availability of water resources. Relevant principles are listed in Table 36 and discussed below.

Table 36 Water resource planning principle for supply system shocks

Title	Principle
SS-1: Stress testing for shocks	Stress testing can be used to test resilience and inform a plan for unplanned supply system shocks.

Discussion of principle: Stress testing can be used to identify supply system vulnerabilities. That is, asking the question of what supply conditions would look like, and how the water service provider might respond, if part of the supply system were to suddenly no longer be available to use for a given period of time. This could include, for example, testing what would happen if a supply catchment were unable to be used for several months due to a bushfire. It could also include testing what would happen if a desalination plant were to be offline due to storm damage, or if a major water main were damaged due to a landslip. Such events are highly unlikely, but they have been known to happen.

7.6 Supply system contingencies

What is it? Allowing for uncertainties through deliberate inclusion of contingencies in the planning process.

Why is it relevant to urban water resources planning? Improving the transparency of any contingencies will promote a more informed discussion about supply system risks. It allows unquantifiable or unknown risks to be mitigated on a precautionary basis. Even when a very conservative appetite for risk is adopted, there is still likely to be a residual water supply risk that is unknown. Relevant principles are listed in Table 37 and discussed below.

Table 37 Water resource planning principles for supply system contingencies

Title	Principle
SC-1: Transparent contingencies	Any assumed contingencies in the water resource planning process should be transparent to decision-makers.
SC-2: Robustness reduces need for contingencies	The more robust a supply system is, the less need there is for water resource planning contingencies.

Discussion of principles:

Transparent contingencies: Contingency planning can be informed by considering, across the whole planning process, (i) what are the potential risks that the planning process has not allowed for, (ii) how they might affect supply system outcomes if they were to eventuate and (iii) the time and capacity to respond to those risks through other means, such as implementing contingency supply measures.

There are various ways in which supply system contingencies can be incorporated into water resource planning. Ways that it has been done in the past include:

- Setting aside a drought reserve volume in storage;
- Assuming that water restrictions generate no demand reduction benefit; or
- Adopting a higher emissions scenario for climate change projections or higher population growth than suggested by current best available information.
- Where a supply system allows, setting aside a drought reserve volume in storage is arguably the most transparent way to incorporate a contingency into supply system planning and management. This is because it is visible, and can be directly linked to a lead time available to implement emergency responses, if that contingency volume is needed. There is no standard duration of supply associated with a drought reserve, and it will be dependent on local climate conditions and the lead times required for emergency response options.

Robustness reduces need for contingencies: The more robust a supply system is, the less need there is for water resource planning contingencies. Having diverse supply sources with greater resilience to input uncertainties means that if one source is adversely affected by one risk, it is still likely that the other supply sources can maintain adequate supply.

8. SELF-ASSESSMENT CHECKLIST

Table 38 is a checklist of yes/no questions that can be used by a water service provider to quickly confirm what they need to consider before they start their urban water planning exercise, or to check for gaps in their existing planning approach.

Table 38 Self-assessment checklist for urban water resources planning

Area and Item	Reference section in the Framework
Understanding your current supply system	
Understand where your supply system is metered?	4.1
Quality checked your input data?	4.1, 4.10
Have a process in place to continue to check that input data and monitor it for anomalies?	4.1, 4.10
Fitted a climate dependent demand model?	4.1
Identified your choice of demand model type(s) (bulk water regression model, end-use model, econometric model, agent-based model)?	4.1
Classified your water use by customer type and into demand for drinking water and non-drinking water purposes?	4.1, 6.1
Understand your legal entitlements to water resources?	4.2
Documented supply system operating rules and the assumptions behind those rules?	4.2
Identified any operating rules that are not represented by water resource models, but which may influence water resource planning outcomes (e.g. water quality triggers)?	4.2
Identified any recent historical changes in operating rules, or deviations from those operating rules?	4.2
For systems with storage, clearly identified your minimum operating volume, maximum operating volume, and full supply volume?	4.2
Estimated current water availability?	4.3
Estimated the proportion and volume of supply available from climate independent water sources?	4.4
Defined the role of climate independent water sources for your supply system (baseload vs contingency supply)?	4.4
Understand any constraints on the availability of climate independent water sources?	4.4
Classified the quality and identified the volume of all available water sources, including those with a quality not suitable for drinking water?	4.5
Identified the spatial and temporal distribution of all available water sources?	4.5
Understand your regulatory requirements for water quality for drinking and non-drinking water purposes?	4.5
Identified ownership and responsibility for non-drinking water sources?	4.5

Identified a design standard (level of service objective) for non-drinking water supply in collaboration with end users?	4.5
Estimated if and when non-drinking water sources would be exhausted, and how much additional demand could return to the drinking water system for non-drinking uses at these times?	4.5
Developed a modelling strategy to assess the implications of supply from non-drinking water sources to water users connected to the drinking water system?	4.5
Identified the current level of risk of your supply system to climate variability?	4.6
Selected a technique to characterise climate variability commensurate with that level of risk?	4.6
Selected a modelling platform, time step, spatial extent, and level of complexity suitable to the supply system characteristics and the intended use of the model?	4.7
Developed a data preparation and water resource modelling approach appropriate to the degree of non-stationarity of model inputs and supply system memory in storage?	4.7
Verified the model behaviour against recent historical behaviour?	4.7
If generating stochastic data, identified a suitable reference dataset and model form, verified model performance against that dataset, checked cross-correlation of variables is preserved, and that data persistence over different time scales is preserved?	4.8
Identified any data or information constraints that inhibit water resource planning decision making?	4.10
Understanding your water supply needs	
Identified performance metrics and ways to measure them?	5.1
Considered performance metrics beyond yield and reliability of supply?	5.1
Defined and estimated critical human water needs?	5.1
Developed a plan to meet those critical human water needs at an acceptable level of risk?	5.1
Have an ongoing community education and consultation strategy in place?	5.3
Consulted specifically with the community about acceptable levels of risk for water supply, and willingness to pay to avoid those risks?	5.3
Have broad agreement from the community about the adopted level of service objective and any other performance objectives?	5.3
Tested option preferences, and the suitability of the preferred water resource strategy?	5.3
Future demand and future water availability	
Considered population projection uncertainty?	6.1
Estimated the potential for drinking water demand substitution with supply from non-drinking water sources?	6.1
Considered potential changes in per capita or per connection residential water use?	6.1

Projected future non-revenue water (or identified potential changes to assumed percentage losses of water)?	6.1
In towns with a high proportion of water use by major industrial customers, projected major industrial water demand?	6.1
In towns or cities with a high number of visitors (relative to the permanent population), considered whether the proportion of demand from visitors is expected to change?	6.1
Incorporated the impact of projected climate change on the above demand projections?	6.1, 6.2
Made any necessary adjustments to water resource planning inputs to allow for historical climate change, and established a suitable local climate baseline?	6.2
Considered which emissions scenarios to adopt, and which global climate model and regional climate model (if applicable) outputs to adopt?	6.2
Understand the levels of confidence associated with the climate model outputs being used?	6.2
Identified a climate change impact assessment approach?	6.2
Identified and assessed the risks to shared water resources from other uses?	6.3
For supply systems with forested supply catchments, identified and assessed the risks of past and future bushfires to water resources?	6.4
Identified any historical shifts in rainfall-runoff or rainfall-recharge response during and after extended drought, and considered the potential risks of this occurred under projected hotter and drier climate conditions?	6.5
Decision making	
Considered the robustness of those performance metrics?	7.1
Considered how adaptability can contribute to robustness?	7.1
Adopted a decision making framework that can support effective decision making given the number of input scenarios and response options to consider?	7.2
Identified where there is insufficient information to enable effective decision making, and developed a strategy to obtain that information?	7.2
Have a water resource model with a level of complexity that can support the decision making framework that has been adopted?	7.2
Developed and implemented an adaptive planning framework that monitors supply system inputs, and actions when supply system inputs deviate significantly from assumed inputs for planning?	7.2, 7.4
Developed and implemented an adaptive planning framework that monitors supply system behaviour, and triggers or defers actions based on that behaviour?	7.2, 7.4
Preserved the design intent of operational triggers over the planning horizon, and across both drought planning and long-term water resources planning?	7.4

Transparently reported any design drought assumptions?	7.4
Identified the lead time for response options, and any actions to reduce those lead times?	7.2, 7.4
Identified potential supply system shocks, stress tested the robustness of the supply system to potential shocks, and developed a plan of action to either improve robustness or respond to those shocks?	7.5
Transparently identified assumed contingencies in the planning process?	7.6

9. FUTURE RESEARCH AND INVESTIGATION PRIORITIES

The following research and investigation priorities have been informed by the knowledge gaps discussed in the specialist topic areas.

1. Continued rollout of **smart meters** to help water service providers better understand water use behaviour at finer temporal and spatial scales, and better inform end use demand models.
2. The development of **uniform water restriction policies** in homogenous climate regions within State and Territory boundaries in Australia and New Zealand, similar to the approach used in Victoria.
3. Continued research into **paleoclimate reconstructions** to improve their quality, and temporal and spatial coverage.
4. The creation of a **national community of practice** for water service providers who use the Source modelling platform to share knowledge and experience of its use for water resources planning.
5. Confirmation of the practical value of **stochastic data for smaller urban supply systems** through case studies.
6. The development of **application-ready stochastic climate datasets** under current conditions across all of Australia and New Zealand, similar to what has recently been made available for New South Wales.
7. The cataloguing of **existing performance standards** for urban water supply systems in Australia, New Zealand, and internationally, including the rationale for their adoption, to provide current benchmarks for urban water service providers.
8. Continued research into our understanding of how the **characteristics of extreme drought** may or may not change **under projected climate change**, as this is currently poorly understood.
9. Continued research into the potential causes of the observed **shift in annual rainfall-runoff response in some urban water supply catchments during and after extended drought**. This includes the variance in time frames to return to a pre-drought state, and further development and case studies to improve the uptake of the tool for water service providers to monitor this risk.

10. GLOSSARY

The following glossary of terms is provided to aid interpretation of the Framework, and to assist with communication of the concepts in this framework to customers, government regulators, and the general public.

Where these terms have already been defined in your jurisdiction, defer to the definitions and terms used in your jurisdiction. These terms have been defined by drawing on Erlanger and Neal (2005), the Bureau of Meteorology's Australian Water Information Dictionary, the Australian Bureau of Meteorology's Climate Glossary, the Murray-Darling Basin Authority's Water Management Glossary, State Government guidance (e.g. DELWP, 2021), and water service provider plans (e.g. Greater Western Water et al., 2022).

The glossary is followed by terms that should be avoided because more precise terminology is available, or because the concepts implied in the terminology are at odds with the risk-based approach to urban water resources planning outlined in the Framework.

10.1 Glossary of terms

Adaptability: The ability of a supply system to adjust to changes in input conditions, to maintain an acceptable performance. Examples of adaptability for supply systems include desalination plants designed with the option to add more production units at low additional cost, or reservoirs built to allow their storage capacity to be increased without compromising dam safety.

Annual exceedance probability (AEP): The likelihood of an event in any given year. This can be expressed as a percentage (e.g. a 1% AEP drought) or as a chance of occurrence (e.g. a 1 in 100 AEP drought) provided that any representation as a chance of occurrence is clear that this is an annual likelihood, not a recurrence interval.

Bias correction: The removal of systematic differences between modelled and observed behaviour, often associated with the removing biases in climate models.

Blue space: Healthy wetlands, lakes, and waterways within an urban setting that are associated with improved health and wellbeing for the community, including urban heat reduction.

Buffer storage: see contingency storage

Carryover: Water that has been harvested in one accounting period, and held in storage for use in subsequent accounting periods. This can include water held within a water service provider's storage or share of storage capacity. Water carried over is subject to losses, including evaporation and reservoir spills, and in some shared supply systems may also be subject to volumetric limits. Urban water supply systems are often classified as having no carryover (for supply systems with no appreciable storage), seasonal carryover (for supply systems which can harvest water in one season for use later in the year), single-year carryover (for supply systems that can harvest water in one year for use in the next year), and multi-year carryover (for supply systems that can harvest water in one year for use in following years).

Climate baseline: A reference dataset of climate information, often corresponding to a particular period of time in history, from which changes in climate can be assessed.

Climate independent water sources: Water that is produced largely or completely independently of climate, primarily desalinated water and recycled water.

Contingency: A provision for a possible event, especially one which lies outside of the events that have been planned for.

Contingency storage: A volume of water reserved in a storage to provide a contingency. The size of a contingency storage depends on the lead time required to implement emergency demand and supply measures once the top water level of the contingency storage has been reached.

Critical human water needs: At a minimum this includes water to sustain life for drinking, cooking, and sanitation, including any water required for water treatment and delivery. Beyond this basic requirement, the understanding of critical human water needs is subjective, and will be specific to each supply system. It may also include water for essential services, such as water use required for power generation, or any other sectors of the economy regarded as essential (e.g. for hospitals, some or all industries, some or all businesses, to preserve important community assets, etc.). For urban supply systems that also supply rural customers, it might also include supply for essential stock and domestic use to those customers. Alternative terms: **Essential minimum supply volume**.

Decision variables: The variables which are being adjusted to obtain an optimum solution for a performance objective during optimisation.

Decision space: The information being generated for consideration in decision-making.

Downscaling: A method that produces local to regional-scale climate information from larger scale climate models or data analyses. Different methods include dynamical, statistical, and empirical downscaling.

Drought: A long period of abnormally low rainfall, expressed by the Australian Bureau of Meteorology as a serious or severe rainfall deficiency for a period of three months or more. A serious rainfall deficiency is where rainfall lies above the lowest 5% of recorded rainfall, but below the lowest 10% of recorded rainfall for the period in question. A severe rainfall deficiency is where rainfall lies below the lowest 5% of recorded rainfall for the period in question. Drought declaration is the responsibility of State and Federal governments which must consider other factors apart from rainfall, such as the impact of the rainfall deficiency on the community.

Full supply level and volume: The water level (and its associated volume) at which a water storage begins to spill. This differs from the **maximum operating level and volume** (see below).

Headworks: Dams, weirs, and associated works used for the harvest and supply of water.

Hydro-economic model: A water resource model that includes both water volumes and the financial costs associated with supply system operation and augmentation.

Integrated water management: A process that brings together all stakeholders involved in the planning and management of all water across the entire water cycle, to ensure that the liveability, resilience, and sustainability outcomes that the community is seeking are maximised across cities and regions.

Level of service: The performance of a supply system in relation to water delivery to customers over the long-term.

Level of service objective: The desired (or target) performance for water delivery to customers from a supply system over the long-term, as agreed with customers and (where relevant) government regulators. This has historically been expressed as a target reliability of supply. Performance objectives for a supply system can extend beyond the level of service to also include other measures such as liveability and sustainability.

Liveability: Factors that improve the quality of life or wellbeing of the inhabitants of a city or place. It includes supporting active healthy lifestyles, environmental values, providing resilience to chronic and acute urban heat events, and supporting social wellbeing.

Managed aquifer recharge: The delivery of water to a groundwater storage (aquifer).

Minimum operating level and volume: The level of the lowest outlet of a storage, and its associated volume, or the level at which water quality or any other physical constraints limit the ability to draw water from the storage for its intended use. This water cannot be accessed under normal operating conditions. Water below the minimum operating level can sometimes be accessed using temporary pipes and pumps.

Maximum operating level and volume: The normal maximum operating water level of a water storage (and its associated volume) when not affected by floods. It excludes any storage capacity set aside above this level for downstream flood protection or for dam safety.

Multi-replicates: Alternative model input sequences, typically under alternative climate sequencing.

Non-revenue water: Losses from a supply system including real losses such as supply system evaporation from storages, pipeline leaks, water lost in water treatment processes, etc. plus apparent losses, such as metering inaccuracies and unauthorised water consumption.

Paleoclimate proxy record: An estimate of climate conditions, prior to the start of instrumental climate records, inferred from non-climate sources such as tree ring growth, coral growth, stalactites and stalagmites, ice cores, etc. It is referred to as a proxy record because it is inferred rather than directly measured.

Performance objective: Any objective related to the performance of a supply system. Performance objectives can be broader than level of service objectives, because they can extend beyond the water supply service provided, to also include broader community objectives.

Portfolio: A collection of supply sources, supply system configurations, and operating rules for a supply system over a planning horizon. A supply system portfolio recognises that more than one source of supply may be needed at any single point in time, and that changes in those sources of supply may be needed at future points in time. Different portfolios can be compared for their efficacy over a planning horizon.

Regret: The cost associated with making a sub-optimal decision. This arises in the context of future uncertainty when a decision is made on the basis of one scenario but another scenario eventuates, or on the basis of many scenarios but only one of those scenarios eventuates.

Reliability: The proportion of time that a given state is achieved. This is typically associated with reliability of supply, which is the proportion of time that a given volume can be supplied without restriction or shortfall. It can also be associated with the proportion of time that an operational trigger is reached, or that a performance target is achieved.

Replicate: An alternative representation of a given sequence of data. Multi-replicate modelling involves either shuffling the order of input data or generating stochastic data of the same length as a reference data sequence.

Reserve storage: A volume of water set aside within a storage as a contingency for conditions which fall outside of assumed supply system behaviour. Also known as a **contingency storage**.

Resilience: The ability of a supply source or supply system to recover its performance quickly after disruption. Some deterioration of performance can occur, but not to the point where it is a permanent and irreversible deterioration. A supply system would be considered resilient if it is able to recover from an event that threatens that performance, such as a drought. A supply source would be considered resilient if it recovers to its pre-drought water availability after a drought. Permanent loss of performance implies that a supply system is not resilient – such as the permanent loss, during a drought, of urban parks and gardens that support liveability, or the permanent migration of customers to another city or town in response to drought.

Restrictable demand: The component of demand that can be subject to water restrictions (defined below). It typically includes outdoor water use from the drinking water supply system.

Risk: The combined likelihood and consequence of an event. It represents the chance of injury or loss. In relation to water supply, the chance of injury or loss is the possibility of not meeting performance objectives.

Robustness: The ability of a supply source or supply system to withstand different input conditions without unacceptable deterioration in performance. For example, a supply system would be considered robust in the face of drought if it can maintain performance through the use of climate independent water sources, contingency supply measures, voluntary demand reduction, etc. The adaptability of a supply system can contribute to its robustness.

Scenario neutral: A planning approach which assumes that all scenarios are equally plausible and unique, and therefore should all be considered, rather than relying on one or a few representative scenarios.

Stochastic data: Synthetic data, generated using a mathematical model, that has the same statistical properties as a reference dataset.

Unrestrictable demand: The component of demand that cannot be subject to water restrictions. It typically includes water for commercial and industrial purposes, and for in-house use.

Water restrictions: Temporary but mandatory restrictions on how or when water can be used. For the purposes of this Framework, these exclude permanent water saving measures or permanent water efficiency measures.

Water service provider: A provider of water supply to customers, which can encompass water utilities owned by State and Territory governments, local government operators, or private companies.

Yield: The average annual volume that can be supplied by a water supply system subject to an adopted set of operating rules and a demand pattern, at a given level of service. Yield is always associated with a likelihood.

10.2 Terms not recommended

Average recurrence interval: This is the interval over which an event would be expected to occur once on average. It has historically been used to describe extreme droughts as a “1 in 100 year” or “1 in 1000 year” event. In preference, the annual exceedance probability should be adopted, to emphasise that the likelihood of an event in any given year is being expressed, not how frequently it could occur.

Dead storage: Although commonly used by water industry practitioners, the terms minimum operating level and minimum operating volume are more precise and easier to communicate to stakeholders.

Drought proofing: This refers to the adoption of supply enhancement measures to reduce the risk of a supply shortfall to zero risk. Past experience and research indicates that there is always the possibility of a drought more severe than the most severe drought being considered. What was previously considered drought-proof can become no longer drought-proof. Recommended alternative descriptions include being transparent about the likelihood associated with any design drought assumptions used in the planning process, and the use of terms such as “climate independent water sources”, “enduring supply”, and “climate resilience” to describe supply systems that are resilient to drought.

Potable and non-potable water: The equivalent terms drinking water and non-drinking water have been adopted in this Framework. Potable and non-potable water are less familiar terms for the general public.

Safe yield, secure yield: These terms have historically been adopted because they utilise more conservative yield assessment criteria. However, they imply that the risk of a supply shortfall is zero. Past experience and research indicates that there is always the possibility of a drought more severe than the most severe drought being considered, and that what was previously considered safe and secure can become no longer safe and secure. Recommended alternative descriptions include using the term supply system yield (or just yield in the context of discussion of a supply system), and being clear what design assumptions are associated with any individual yield estimate.

Sustainable yield: All harvesting of water should be sustainable, hence it is implied that urban supply system yield is always sustainable unless otherwise stated. Where this is not the case, performance metrics for sustainability can be used to indicate that harvesting of water is not sustainable.

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