Sufficiency and Resilience of Public Water Supply

27 June 2025

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Acronyms

AMP	Asset Management Plan
AWWA	American Water Works Association
BAU	Business as Usual
BCP	Business Continuity Planning
BSR	Building Safety Regulator
CEN	European Committee for Standardization
CENLES	European Committee for Electrotechnical Standardization
CCW	Consumer Council for Water
DWI	Drinking Water Inspectorate
DWSP	Drinking Water Safety Plan
EPA	United States Environmental Protection Agency
ERP	Emergency Response Plan
GDP	Gross Domestic Product
GSS	Guaranteed Standards Scheme
IWA	International Water Association
IWRM	Integrated Water Resources Management
KPI	Key Performance Indicator
LTA	Long Term Average
LOS	Level of Service
MOSL	Market Operator Services Limited
NIAC	National Infrastructure Advisory Council
NIC	National Infrastructure Commission
OECD	Organisation for Economic Cooperation and Development
PCC	Per Capita Consumption
PSR	Priority Services Register
RRA	Risk and Resilience Assessment
SCADA	Supervisory Control and Data Acquisition
SDBI	Supply Demand Balance Index
SEMD	Security and Emergency Measures Directive
SoSI	Security of Supply Index
UE	Uisce Éireann (formerly Irish Water)
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research
UN	United Nations
UNICEF	United Nations Children’s Emergency Fund

US EPA	United States Environmental Protection Agency
WAFU	Water Available For Use
WHO	World Health Organisation
WIA	Water Industry Act
WRc	Water Research Centre
WRF	Water Research Foundation
WRI	World Resources Institute
WRMP	Water Resource Management Plan
WSEF	Water Supply Evaluation Framework
WWF	World Wildlife Fund
WWRAG	Water and Wastewater Resilience Action Group

1. Expectations of resilience and sufficiency

1.1 Introduction

The National Infrastructure Commission (NIC) recently published a report on developing resilience standards in UK infrastructure. The report concludes that the government should publish resilience standards for the digital and telecoms, energy, transport, and water sectors by 2025, and issues a number of recommendations specifically relating public water supply and comments on the limitations of existing standards and regulatory incentives. As the body delegated by the Secretary of State to ensure sufficiency of supply, and in response to the NIC's call that by December 2025 "*[t]he Department for Environment, Food and Rural Affairs, Ofwat, the Environment Agency and the Drinking Water Inspectorate should collectively identify gaps where resilience standards would be appropriate*", the DWI has commissioned WRc to review international standards and approaches to measuring and ensuring resilience and sufficiency of public water supply. Given the driver for this study, the project shall not explicitly consider security and sufficiency of private water supplies (although the powers and duties prescribed by the Water Industry Act are acknowledged).

The idea of a standard approach for measuring and assessing resilience and sufficiency has developed momentum since Water and Wastewater Resilience Action Group (WWRAG) was created in 2016 to define qualitative standards, look at the picture across England and Wales and share best practice. The water industry also commissioned Atkins via UKWIR in 2016 to report on resilience performance measures, costs and stakeholder communication to form the industry's response to Ofwat's consideration of how measures of resilience might be included in Periodic Review 2019 (UKWIR, 2017). Similarly, CEN – European Committee for Standardization / CENLES – European Committee for Electrotechnical Standardization recommended that the EU explicitly reference standardisation in their Water Resilience Strategy to ensure that policy actions are technically supported and aligned with existing standards (CENELEC, 2025).

1.2 Methodology

The quick scoping review sought to answer the following primary question:

What can the UK learn from how the resilience and sufficiency of water supply, from source to tap, is defined, measured and governed internationally?

This was supported by secondary and tertiary questions and subtopics to help focus the search. The full set of secondary and tertiary questions and subtopics can be found in Appendix A, including some topics that were agreed to be out of scope.

1.2.1 Quick scoping review

The review was split into the following three sections:

Country-by-country search

A country-by-country search was initially undertaken to find examples of how resilient and sufficient water supplies are governed internationally. Fifty jurisdictions (including countries and states) were selected for this review and were chosen as they had a high GDP and were places where customers receive a near continuous supply of treated water from a third party.

Academic and grey-literature search

Academic literature was sought using the academic search engine BASE[1], into which relevant search strings were fed. A list of search strings is available in Appendix B.

Grey literature was found via internet searches, as well as through organisations such as WHO, the UN, IWA. Through this, industry reports, presentations, conference proceedings, and conference papers were found.

Collation of documents which outline the UK framework

Secondary legislation, underlying guidance, and other relevant material was identified to help explain the current UK standards for, performance of, measurement of, and legislative powers for resilience and sufficiency of supply in England and Wales. This was extended to cover Scotland, Northern Ireland, the Republic of Ireland, and other members of the British Isles.

Screening

Identified documents were then screened to determine their relevance to the project. This included:

1. Primary screening – inclusion/exclusion based on whether title was relevant

2. Secondary screening – inclusion/exclusion based on whether abstract/executive summary was relevant

3. Tertiary screening – inclusion/exclusion based on whether main text was relevant

Relevant excerpts were then identified from documents that had passed all three levels of screening.

The full Research Protocol can be found in Appendix B.

[1] https://www.base-search.net/Search/Advanced

1.3 Defining a resilient and sufficient water supply

1.3.1 What is resilience?

The definition of resilience as it is commonly used in the water industry today originated in ecology with the concept first being articulated by Holling (1973), who described resilience as the ability of ecosystems to absorb disturbances and still maintain their essential functions. Use of the term has subsequently been expanded and it has been applied across a range of domains, including climate adaptation, development, security, and water resource management. (Duijnhoven & Neef, 2014; Pahl-Wostl & Knüppe, 2016)

Resilience is also often distinguished between 'hard' and 'soft' forms. Hard resilience refers to the physical strength of infrastructure or institutions under pressure, whereas soft resilience involves adaptability, flexibility, and the capacity of systems to recover from disruption through social or organisational mechanisms (Proag, 2017). In some areas, hard resilience is categorised differently, for example as strength or robustness.

Barriers

Inconsistency in terminology is a barrier to universal approaches to resilient and sufficient water supply. The lack of consistency and agreement within the literature on the definition of resilience between major international bodies has been noted by a number of authors.

For example, the WRF observed that a "*lack of consistent definitions for reliability, resilience, and sustainability (RRS) makes it difficult to incorporate these concepts into the water supply planning process*" (Water Research Foundation, 2018), while the *Targeted review of asset health and resilience in the water industry* conducted for Ofwat in 2017 also concluded that there was "*no consistent definition of asset health across all companies*" in England and Wales and that this was also the case internationally (Ofwat, 2017). This is demonstrated in Appendix C, which lists a variety of international resilience definitions. Furthermore, the definition for resilience changes depending on context, for example in water resources resilience is typically the ability to withstand drought (Water Research Foundation, 2018). Despite this, the WRF found that the resilience definition established by the Rockefeller Foundation was cited by several organisations (Water Research Foundation, 2018). This states that "*resilient systems withstand, respond to, and adapt more readily to shocks and stresses to bounce back stronger after tough times, and live better in good times*" (Rockefeller Foundation, 2015). Similarly, some have argued that a resilient system is in a perpetual state of flux, enabling it to continually adjust and adapt to new disturbances and a changing context (Water Research Foundation, 2018).

It has also been noted that short-term stability and resilience can obscure the adaptive, open-ended nature of systemic resilience. Currently, many water systems focus on short term stability and resilience and are not focussing on long-term transformation or adaptation (Water Research Foundation, 2018).

It should also be noted that the meaning of resilience varies linguistically, as seen in Table 1.1. As such, variations in the definition and interpretation of resilience may be cultural as well as discipline related (Water Research Foundation, 2018).

Table 1.1 The meaning of resilience between language groups (Hirano & Latorre, 2017)

Language	Term	Meaning
Arabic	Eala alssumud	To withstand
Chinese	Yù zāihài nénglì	Ability to resist disaster
Russian	Zhiznestoykosti	Viability
Dutch	Veerkrachtige	Spring back
Greek	Epanaktikótita	Gain again (ability to return to previous position)
Japanese	Kyo-jin	The state of being tough and supple
Thai	Kwam samart nai karn prab tua lae fuen tua	Ability to recover and adapt

UK context

Looking specifically within the UK water industry, Ofwat[2] states that "*resilience is the ability to cope with, and recover from, disruption, and anticipate trends and variability in order to maintain services for people and protect the natural environment, now and in the future*" (Ofwat, 2015). This is quite different to the Environment Agency's definition of "*the capacity to maintain essential services under a range of circumstances from normal to extreme*" (Enviroment Agency, 2015). Two important differences are:

- the Environment Agency focusses on 'essential' services while Ofwat can be assumed to be referring to a level of service that water companies are expected to provide;
- the Environment Agency focusses on 'maintaining' services, which is implicitly backwards-looking, while Ofwat is focussed on 'now and the future'.

This differs again to the NIC who defined water resilience as "*the capacity of cities to function in the face of water-related stresses so that those living and working within the city can survive and thrive*". The ability to 'function' could be interpreted as more similar to the Environment Agency's 'essential services', while yet another commonly adopted definition is found in the UK Guidance '*Keeping the Country Running*' *"[r]esilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event" which implies greater focus on avoiding asset failure rather than maintaining a minimum level of service*."

[2] Defined by 2015 Task and Finish Group

1.3.2 What attributes makes a supply resilient?

In order to measure and regulate resilience and sufficiency it is necessary not only to define the end objective but also to understand what this means in practice: what properties of a system should be measured in order to assess whether it is resilient?

Ofwat considers their resilience duty to extend beyond the legal definition in the Water Industry Act (WIA) to include ‘resilience thinking’. It cites the Cabinet Office guidance *Keeping the country running* as an example of a wider systems-thinking approach to protecting essential services such as water. It links this wider view of resilience with a “*shared vision of trust and confidence*” (Ofwat, 2015).

Ofwat states that “*within the context of water systems, resilience is often framed as a system’s ability to cope with or recover from shocks such as floods and droughts, while retaining its essential identity under long-term change*” (Ofwat, 2015). Ofwat defines ‘long term’ in the context of water sector planning and investment as “*25 to 100 years ahead*”.

In its response to Ofwat’s 2015 consultation on reliable services for customers, Water UK highlighted that “*experience from past events and risks provide insufficient evidence to demonstrate resilience into the future*”, going on to state that “*companies should be encouraged and incentivised to plan on the basis of potential future scenarios, taking into account the best available evidence and with an appropriate treatment of uncertainty. In doing so, companies should be better able to take informed decisions that reduce whole-life costs and increase the benefits to society from improved resilience*” (Water UK, 2015).

Academic studies

There have also been academic studies which have sought to define the characteristics of a resilient system. For example, Boltz *et al.* (2019) describes what persistence, adaptability and transformability provides systems, where (Boltz, et al., 2019):

- **Persistence** relates to a system’s ability to “*maintain coherent function under changing conditions and disruption without altering its identity*”, in which it can return to its prior function following external stressors and/or shocks.

- **Adaptability** relates to a system’s ability to “*maintain coherent function by modifying its identity to accommodate change*”, where the system (or its operators) continuously adjusts responses and innovates and reorganises parts of the system in response to external conditions, enabling it to realign with its current equilibrium and sustain its functions.

- **Transformability** relates to a system’s ability to “*change its identity and to establish a new function in a novel equilibrium when pushed beyond the threshold of its present state*”, where the system changes in response to ecological, economic, or social conditions which make the existing system unmaintainable.

Wildavsky proposed the following attributes/principles of resilient (Butler, et al., 2014):

- **Homeostasis** – systems are maintained by feedbacks between component parts that signal changes and can enable learning. Resilience is enhanced when feedbacks are transmitted effectively, such as through real-time monitoring.

- **Omnivory** – where external shocks are mitigated by diversifying resource requirements and their means of delivery, such as having a variety of supply sources.

- **High flux** – the fast movement of resources through a system enabling more resources to be available at any given time to help cope with perturbation. This may include increasing capacity, storage and/or design load.

- **Flatness** – flexible systems are able to cope with surprises and adjust behaviours. Such systems may have sensors equally distributed throughout the system enables a consistent level of service to be provided.

- **Buffering** – sufficient headroom, enabling the system to have additional capacity times of need, increasing its resilience.

- **Redundancy** – a degree of overlapping function in a system permits the system to change vital functions to continue while formerly redundant elements take on new functions. This could include having spare parts on hand in the event of failures.

Butler *et al.* (2016) states that specific performance goals must be met for a system to be classified as reliable, resilient, or sustainable. A variety of system properties can contribute to this, however no one property or group of properties can guarantee that a system will be reliable, resilient, or sustainable (Butler, et al., 2016). Subsequently, Butler *et al.* (2016) states that "*in this respect, continued service delivery could be viewed as an emergent feature of a complex system with multiple interacting properties, and as such, performance may be unknowable when the system is subject to exceptional conditions*" (Butler, et al., 2016).

US EPA Effective Utility Management

The US EPA states that the following ten attributes contribute to an effectively managed utility (EPA, 2024):

- **Community sustainability** – utility takes an active role in promoting and organising community sustainability improvements; manages operations, infrastructure, and investments to support the economic, environmental, and social health of its community; and integrates water resource management with community planning of infrastructure and social and economic development to support communitywide resilience.

- **Customer experience and satisfaction** - reliable and responsive services in line with explicit, customer-derived service levels.

- **Enterprise resiliency** - manages risk to ensure it can continue to operate and provide a water service; responds to, adapts, and recovers from service disruption by understanding relevant trends and forecasts, and by creating and executing response plans in coordination with regional partners

- **Financial viability** – financial charges in line with community expectations that effectively balance long-term debt, capital, operations and maintenance expenditures with revenues and asset values. Revenue is diversified and new capital is raised through new and innovative business and financing models.

- **Infrastructure strategy and performance** – know and understand condition and costs of critical assets; plan, maintain and enhance infrastructure investments to meet long-term needs; develop and implement assets management plan that is aligned with a strategic business plan.

- **Operational optimisation** – incorporating innovative solutions and effectively utilising technology and tools to optimise data management and analysis.

- **Regulatory and reliability performance** – meet/exceed regulatory requirements and provide a reliable service/product, maintaining consistency with customer, community, public health, safety, ecological, and economic priorities.

- **Stakeholder understanding and support** – this facilitates understanding and support from stakeholders and considers the full spectrum of impacts to a diverse set of stakeholders at all stages of decision making to ensure the same level of service and quality for all communities served.

- **Water resource sustainability** – integrated and sustainable water resource management which considers the utility's role in the water cycle and environment, including long-term integrated water resource planning and equitably meeting customer, community, and ecological water needs.

- **Workforce development** – recruit, develop, and retain a workforce that is inclusive, competent, motivated, adaptive, and reflective of the community they serve where institutional knowledge is retained, transferred, and improved upon over time.

Qualities of a Resilient City in Canada

The Prairie Climate Centre stated that the following qualities compose a resilient city (Prairie Climate Centre, 2017):

a) **Reflective**: Past experiences are reflected and learnt from and leveraged to inform future decision making.

b) **Robustness**: Physical assets are designed, constructed and maintained in anticipation of and to withstand high-impact climate events.

c) **Redundancy**: Additional capacity is built into the system to account for disruptions and surges in demand.

d) **Flexible**: A willingness and ability to adopt alternative strategies in response to changing circumstances or sudden crises. This could include innovative approaches such as new technology.

e) **Resourcefulness**: The public and businesses are aware of climate risks and can adapt to shocks and stresses and can quickly respond to a changing environment.

f) **Inclusive**: Inclusive processes informed by many views to create a sense of shared ownership or a joint vision to build city resilience.

g) **Integrated**: Integrated processes align systems to promote consistency in decision making and investments. This is supported by information sharing between different components of the system, enabling them to function collectively and respond rapidly to events.

1.3.3 Discussion

It is easy to get lost in semantics when attempting to define resilience. This is unlikely to be beneficial, but it is important to acknowledge when assessing existing frameworks and approaches that there may not be a common language or common set of objectives. The DWI is interested in resilience insofar as it ensures continuity and sufficiency of supply to end users. As such, financial resilience, sustainability and, to an extent, corporate, asset and community-related resilience aspects are not of primary concern. In addition, DWI is most interested in what we shall term ‘business as usual’ (BAU) performance: the ability of water companies, ideally through a water supply system, to provide continuous and sufficient supply to customers under ‘reasonably foreseeable or predictable’ conditions and events over a medium-term planning horizon. This report will therefore appraise metrics, regulatory approaches and resilience frameworks in this context, as means for measuring and incentivising progress towards continuity and sufficiency of supply, attempting to define the boundaries of what is ‘sufficient’ and ‘continuous’, and what is ‘resilient’ in terms of maintaining this situation under BAU.

1.4 Societal expectations of sufficiency

This section provides an overview of what is likely to be considered to be a sufficient supply of water. Sufficiency is very contextual. For example, what might be considered as an acceptable amount of water to be supplied over the short term is unlikely to be considered acceptable over the long term. Sufficiency is not a defined term in the WIA. As such, one must rely on common usage and understanding. Definitions from common British English dictionaries are presented in Table 1.2 We see that sufficiency is generally associated with being “enough” or “adequate” and that this is often linked to a purpose or need. In the context of water, it is therefore necessary to define both what is enough/adequate (and who decides this) and what purposes are considered to be suitable. A common assumption appears to be that sufficient supply is enough water to meet system demand or, as a minimum, enough supply to meet domestic demand. However, as the WIA defines domestic purposes as "*drinking, washing, central heating and sanitary purposes*" (where sanitary purposes are "*washing/bathing/showering, laundry and toilet flushing*"). Water supply for non-domestic purposes is conditional: water companies must ensure they can meet existing domestic supply before considering connections for non-domestic uses and non-essential (non-domestic) use can be restricted. As such, there is an argument that sufficient supply only should need to be adequate for domestic purposes. However, this approach has not generally been taken by regulators in the UK who consider temporary use bans and restrictions as a customer service failure and evidence of an insufficiently resilient supply.

Table 1.2 English dictionary definitions of sufficiency

Source	Definition
Oxford English Dictionary	The condition or quality of being sufficient for its purpose or for the end in view; adequacy; (A) sufficient number or quantity of; enough
Collins English Dictionary	Sufficiency of something is enough of that thing to achieve a purpose or to fulfil a need.
Cambridge English Dictionary	An amount of something that is enough for a particular purpose
Longman Dictionary	The state of being or having enough

The WHO defines four levels of water accessibility, use and quantity (WHO, 2020):

- People with **inadequate** access have no household water security: the quantities collected are insufficient, the effort taken to acquire water is excessive, the source may not be reliable, and safety of water cannot be assured.
- People with **basic** access have basic household water security, provided that water is available every day, and that quality can be assured at source and protected during subsequent handling and storage. Households with basic access may increase their household security by relying on other sources.
- People with **intermediate** access have household water security: sufficient water should be available for all personal domestic needs, and safety can be more readily assured if the supply is available for several hours during normal waking hours and preferably 24 hours a day. For households with intermittent supply, the level of water security may be improved through coping mechanisms such as increased storage or alternative sources, although these could have financial and health implications.
- People with **optimal** access are fully water secure: quantity and continuity of water are likely to be adequate for domestic water needs, provided that quality is assured, current

services are sustainable, and future growth in demand and threats from climate change can be managed.

This is expanded upon in Table 1.3.

Table 1.3 Water access, adequacy and level of health concern (WHO, 2020)

Access level and typical volumes of water used in the home	Accessibility of water supply	Adequacy for health needs	Level of health concern
Inadequate access (quantity collected can be below 5.3 l/person/day)	More than 1,000 m in distance or 30 minutes total collection time	**Drinking** – cannot be assured **Cooking** – cannot be assured **Hygiene** – cannot be assured at the home, compromising food hygiene, handwashing and face washing; other hygiene activities have to be undertaken away from the home	Very high
Basic access (average quantity unlikely to exceed 20 l/person/day)	100 to 1,000 m in distance or 5 to 30 minutes total collection time	**Drinking** – should be assured **Cooking** – should be assured **Hygiene** – food hygiene, handwashing and face washing may be assured; bathing and laundry cannot be assured at the home but may be carried out at water source	High
Intermediate access (average quantity about 50 l/person/day)	Water delivered through one tap on- plot, or within 100 m or 5 minutes total collection time	**Drinking** – assured **Cooking** – assured **Hygiene** – all food hygiene, handwashing and face washing assured under non-outbreak conditions; enhanced hygiene during infectious disease outbreaks not assured; bathing and laundry at the home should also be assured	Medium
Optimal access (average quantity more than 100 l/person/day)	Water supplied through multiple taps and continuously available	**Drinking** – all needs met **Cooking** – all needs should be met **Hygiene** – all food hygiene, handwashing and face washing needs should be met, including for bathing and laundry at the home, and household cleaning	Low

As mentioned, in England and Wales, water undertakers have a statutory duty to provide sufficient water to meet its customers' domestic needs (Ofwat, 2025; UK Government, 2025). The legal requirements (10 l/p/d for up to 5 days, 20 l/p/d beyond that) are set out in the SEMD (see section 1.4.2). Optimal access, as described above, could be interpreted as 'sufficient' in the context of the UK water sector, while intermediate access describes a situation more akin to emergency water supplies in the UK. One definition of sufficiency could therefore be 100 l/p/d, except in the event of emergency outages, in which case 50 l/p/d should be ensured (WHO, 2014).

1.4.1 Sufficient pressure

When discussing minimum pressure requirements, the WHO give the example of 14 m head being maintained at all points in the distribution system and 35 to 52 m head at all residences.

Customer research by Scottish Water found that expectations regarding water pressure were high, with many stating that as living standards had improved and that it was now unacceptable to put up with low water pressure. This was particularly true for customers living within modern[3] housing stock. Many expected to be able to use multiple water using devices at once e.g. for the both the shower and washing machine to be in use at the same time (Scottish Water, 2021; Turquoise, 2018). It was cited that people nowadays are time-poor and do not want to have to wait to be able to use certain water-using devices due to the use of others (Turquoise, 2018).

Over the last 10 years, when consumers were asked whether they were satisfied with the water supply pressure they received, an average of 88% of respondents confirmed they were, but there is evidence of a decrease in satisfaction over the same time period. Satisfaction was found to be similar for domestic and non-domestic customers (CCW, 2024). Scottish Water's customer research also found that customers felt that it was "admirable" that Scottish Water's aim to provide 2 bar (20.4 m head) of pressure to the property boundary. A common view was that 1 bar (10.2 m head) was insufficient as combination boilers often specify higher than this. However, others felt that 20.4 m head was too high as boilers made noises above 1.5 bar (15.3 m head). Many were concerned that raising the pressure might lead to more bursts and leaks (Turquoise, 2018).

Affinity Water suggested that the Guaranteed Standards Scheme (GSS) payment for low pressure is designed as a rebate for customers permitted under the WIA to receive low pressure "*nothing shall require a water undertaker to provide a supply of water at a height greater than that to which it will flow by gravitation*" and, as such, should exclude temporary instances of low pressure which are not already excluded as a result of 'necessary works' (Affinity Water, 2023).

Defra has decided differently, instead saying that multiple repeated occurrences of low pressure within a year should warrant additional payments to reflect the greater disruption. Defra's proposed changes to the GSS (Defra, 2024) includes the removal of this limit, replaced with a

[3] "modern" is not defined

limit of 5 payments a year. Customers on the DG2 register (properties at risk of low pressure) would also automatically receive £250 per year.

When considering sufficient water pressure, it is necessary to consider all users of the water system. For example, what is sufficient for domestic purposes may not be sufficient for firefighting. The National Guidelines for Firefighting state that (Water UK, 2007):

> "*Subject to the following provisions of this section, it shall be the duty of a water undertaker to cause the water in such of its water mains and other pipes as*
>
> *(a) are used for providing supplies of water for domestic purposes; or;*
>
> *(b) have fire-hydrants fixed on them, to be laid on constantly and* ***at such a pressure as will cause the water to reach to the top of the topmost storey of every building within the undertaker's area.***
>
> *except in certain circumstances or when work is being undertaken […] however the Water Companies do not have powers to require developers to size mains for firefighting purposes*".

Water companies are not required to **maintain** an increased the level of in order to meet this requirement but are required to take action to ensure (within best endeavours) that it is met, potentially to the detriment of other customers:

> "*(1) If a fire and rescue authority requests a water undertaker to provide a supply and pressure of water for the purposes of extinguishing a fire* ***that is greater than the undertaker would otherwise provide****, the undertaker must take* ***all necessary steps*** *in order to do so.*
>
> *(2) For the purposes of complying with its obligation under subsection (1) a water undertaker may shut off the water from the mains and pipes in any area.*
>
> *(3) No authority or person is liable to any penalty or claim arising because of anything done by a water undertaker in complying with its obligation under subsection (1).*
>
> *(4) A water undertaker commits an offence if, without reasonable excuse, it fails to take any step which it is obliged to take under subsection (1).*
>
> *(5) A water undertaker guilty of an offence under subsection (4) is liable on summary conviction to a fine not exceeding level 5 on the standard scale.*"

Table 1.4 shows the flows required for firefighting for each building type.

Table 1.4 Minimum supply requirements for fire fighting (Water UK, 2007)

Location	Fire flow required
Housing	Housing developments with units of detached or semidetached houses of not more than two floors should have a water supply capable of delivering a minimum of **eight litres per second** through any single hydrant. Multi occupied housing developments with units of more than two floors should have a water supply capable of delivering a minimum of **20 to 35 litres per second** through any single hydrant on the development.
Transportation	Lorry/coach parks - multi-storey car parks - service stations should have a water supply capable of delivering a minimum of **25 litres per second** through any single hydrant on the development or within a vehicular distance of 90 metres from the complex.
Industry	In order that an adequate supply of water is available for use by the Fire and Rescue Authority in case of fire it is recommended that the water supply infrastructure to any industrial estate is as follows with the mains network on site being normally at least 150 mm nominal diameter: Up to one hectare **20 litres per second**. One to two hectares **35 litres per second**. Two to three hectares **50 litres per second**. Over three hectares **75 litres per second**.
Shopping, offices, recreation and tourism	Commercial developments of this type should have a water supply capable of delivering a minimum flow of **20 to 75 litres per second** to the development site.
Village halls	Should have a water supply capable of delivering a minimum flow of **15 litres per second** through any single hydrant on the development or within a vehicular distance of 100 metres from the complex.
Primary schools and single storey health centres	Should have a water supply capable of delivering a minimum flow of **20 litres per second** through any single hydrant on the development or within a vehicular distance of 70 metres from the complex.
Secondary schools, colleges, large health and community facilities	Should have a water supply capable of delivering a minimum flow of **35 litres per second** through any single hydrant on the development or within a vehicular distance of 70 metres from the complex.

1.4.2 Minimum levels of service during network issues

UK

What is considered the minimum acceptable quantity of water supplied to a person varies depending on context (e.g. high- or low-income country), as well as what is constituted as essential water use. For non-household users the variance is even more significant, and very little literature was identified in this area.

In the UK, the *Security and Emergency Measure Direction (SEMD) 2022* requires that all consumers have access to 10 litres of water for "essential [domestic] use" for every day that they are without a piped supply, and that this must be provided via an alternative means (e.g. bottled water, tanker) within the first 24 hours of losing piped supply (Defra, 2006). If this is for a prolonged time (over 5 days), this volume increases to 20 litres of water for each day without piped supply (DWI, n.d.; Yorkshire Water, 2021).

It is presumed that 10 litres per person per day, used sparingly, was judged to just meet drinking water consumption (~2 litres), culinary uses, basic sanitation (hand washing and limited toilet flushing), but not bathing/showering, clothes washing or automatic dishwashing. The higher amount of 20 litres/person/day after 5 days may be assumed to allow some handwashing of essential garments in addition to personal washing. The SEMD requires water companies to continuously review and revise plans to ensure the provision of essential water supply at all times (Defra, 2006).

We conclude that:

- less than 10 litres per person per day is always deemed insufficient;
- provision of 10 litres per person per day may be tolerated by non-vulnerable consumers in the short term;
- 20 litres/person/day is the minimum level of supply that may be deemed sufficient for life and maintaining basic sanitary needs for a limited period of more than 5 days. There is currently no limit in the UK on how long this limited supply is deemed acceptable, only that such a supply would only be suitable for a limited time.
- a reduction to 20 litres per person per day would be considered unacceptable both by customers and regulators if it were to persist (Defra, 2006; Enviroment Agency, 2015).

International

The *CEO Water Mandate* assert that water allocation regulations should ensure equitable distribution during varying water availability. "*While minimal restrictions may suffice in times of abundance, flat percentage reductions during scarcity can disadvantage certain sectors and communities. Therefore, **regulations should mandate tailored percentage** reductions based on legislated allocations and specific user/sector needs*" (Chapagain, et al., 2021). This is a different approach to the UK where domestic water use is prioritised over other uses such as industrial use.

In the Netherlands, water companies are obligated to provide at least 3 litres of water per person per day for supply interruptions lasting more than 24 hours. This assumes 2 litres for drinking and 1 litre for food preparation (VEWIN, 2025). Furthermore, there is a security of supply design standard which requires water companies to supply a quantity equivalent to 75% of the amount on a ‘maximum day’ within 24 hours of a disruption e.g. failure in part of the supply network (VEWIN, 2025). This is a standard for redundancy and resilience, with the aim of reducing the impact of the failure of one main element (e.g. pumps) on the whole supply network.

South East Queensland Water Regulations 2016 has much stricter requirements. It states that bulk water supply systems should be able to supply enough water so that:

- “medium level” water restrictions on residential and non-residential water use occur no more than once every ten years on average,
- that they do not restrict average residential water use to be less than 140 litres per person per day,
- “medium level” drought restrictions or more last no longer than 5% of the modelled time (typically 6 months of restrictions in 10 years) (Water Regulation, 2016).

Furthermore, the regulations go on to state that the supply network must be able to provide the essential minimum supply volume and that supply is only allowed to be reduced to essential minimum supply once every 10,000 years on average, effectively setting this as the minimum permitted standard, where essential minimum supply is 100 litres per person per day for residential and non-residential water use (Water Regulation, 2016). This is also suggested by Tasmania’s Water Security Strategy, which uses 100 litres per person per day as its critical minimum supply volume where (TasWater, 2023):

- 36 litres is used for a 4-minute shower using a 9 litre/minute shower head;
- an average of 12 litres per person per day is allowed for clothes washing, where 2 to 3 8.5 kg washing machine loads are done every fortnight;
- 6 litres is allocated for outdoors use and cleaning;
- 6 litres is allocated for drinking and food preparation;
- 24 litres is assumed for toilet flushing, where 2 full and 4 half flushes are used per day with a 6/3 litre dual flush toilet;
- 9 litres is allocated for dishwashing

- 7 litres is assigned to commercial activities.

This could be interpreted as considering 140 litres per person per day to be sufficient, and less than 100 litres per person per day to be always insufficient. Water use is typically higher in Australia than the UK. In South East Queensland the most recently available per capita consumption (PCC) rates are 163 l/p/d for residential use (2024) and 242 l/p/d total use (residential and non-household, 2023) (SeqWater, 2024; SeqWater, 2013). It could therefore be argued that a more appropriate benchmark would be that water supply should exceed 86% (140/163 l/p/d) of average demand, 95% of the time.

In Western Australia, the *Water Services Act 2012 Water Services Code of Conduct (Customer Service Standards) 2024* states that "*a licensee must not […] reduce the rate of flow of a supply of water to a customer to below 2.3 litres each minute*". This is in relation to water supply restrictions owing to unpaid water service charges as opposed to interruptions (State of Western Australia , 2024).

Italy has a minimum water supply standard of 50 litres per person per day, and a 'sufficient' standard of 200-280[4] litres per person per day (Acea, 2019; Armeni, 2008). The requirement was introduced as a national decree in 1996 and set the requirement at for at least 150 l/p/d which increased to 200-280 l/p/d in 2005 (Armeni, 2008). An alternative approach to defining emergency/minimum supply is to look at storage requirements (section 8). Design guidelines such as Alberta's Guidelines for municipal waterworks often state water storage requirements should include emergency storage (in this case a minimum of 15% of projected average daily design flow) from which it could be inferred that 15% of projected average daily design flow is a sufficient volume to supply customers during an outage (Alberta Government, 2012).

For everyday water use (not during an emergency), Chenoweth (2008) argues than 85 litres per person per day is needed to meet basic health and hygiene needs (drinking, bathing, toilet flushing), with a total of 135 litres per person per day to support human health and for economic and social development (Chenoweth, 2008). However, this estimate for essential water use (85 litres) is based on the assumption that efficient dual flush toilets are used and that they recycle water used for bathing to flush said toilets, which is not representative of the UK. In this estimate, 52 l/p/d is used for bathing, 20 l/p/d is used for clothes washing, 8.7 l/p/d is used for food preparation and dish washing, 1.6 l/p/d is used for drinking, and 6.4 l/p/d is used for other uses (Chenoweth, 2008). Adjusting this to include toilet flushing would give an estimate closer to 110 l/p/d.

This contrasts significantly with the WHO and UNICEF, who stated that a minimum of 20 litres per person per day is required for domestic hygiene purposes (Howard, et al., 2020). Issues seem to occur when establishing water required for hygiene, as flow rates of water using devices such as taps and showers vary between countries (Chenoweth, 2008). For example,

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4 Last updated in 2008. Since then, water consumption (including supply-side losses) has decreased from 243 l/p/d to 214 l/p/d in 2022. This suggests that Italy defines 'sufficient' water supply as meeting demand.

Australia has minimum water efficiency standards for water using devices and fittings and likely uses less water for hygiene than a country like the UK, which at time of writing does not have minimum water efficiency standards on **all** individual water-using devices.

What is deemed essential use differs amongst consumers. Consumers with impaired mobility, additional medical needs, and additional personal bathing for religious observance may use higher volumes of water to meet their essential needs. This prompts the question, how can essential use be defined equitably if certain consumer groups use significantly more water than others?

Other examples

The Canadian *Water Supply for Public Protection* guide suggested that a reliable supply can be assumed when it is able to provide the maximum daily consumption rate (average rate on maximum day of past 3 years) and water for firefighting at any point in the network. In areas where there is a population in excess of 250,000, the supply network should be able to provide for two simultaneous fires (Fire Underwriters Survey, 2020).

The *California Water Code* states that a water shortage emergency will be declared if a water company finds that the water supply cannot meet the ordinary demands and requirements of water consumers without depleting the water supply to the extent that there would be insufficient water for human consumption, sanitation, and fire protection (California Water Boards, 2024).

The *Japanese Water Supply Act* states that water utility customers should receive a water supply at all times, unless under unavoidable circumstances such as natural disasters. In such a case, the utility may suspend supply and are required to announce what areas are affected and for how long they will be without supply. There was no mention of the provision of an alternative supply (Japanese Legislation, 1957).

Priority uses and vulnerable customers

The SEMD indicates that priority of emergency supplies should be given to "*the domestic needs of the sick, the elderly, the disabled, hospitals, schools, and other vulnerable sectors of the population; and, that regard is had for the needs of non-domestic as well as domestic users*". This is somewhat vague, as it could be inferred that other households do not come under 'other vulnerable sectors of the population'. It also notes that it is up to the water company to identify which non-domestic customers should be prioritised.

An alternative approach is to prioritise water allocation according to use. For example, during or leading up to a water shortage, the Netherlands prioritises ensuring safety against flooding and preventing irreversible damage, utilities, small-scale high-quality use, and then other needs (Water Decree, 2009). With respect to the utility, priority should be given to ensuring the supply of drinking water and then ensuring the supply of energy (Water Decree, 2009).

Communication

When considering sufficiency during network issues it is also essential to consider communication. The public's expectations for sufficient supply, perception of a water utility's trustworthiness and their satisfaction with water and wastewater services is intrinsically linked to the amount of notice they're given and how their expectations are managed through local and national communication. For example, there is likely to be more acceptance of temporary usage restrictions or reductions in levels of service if this is normalised through centralised communication (e.g. in Australia) and the impacts of disruption are often significantly reduced if sufficient notice is given prior to disruption. For example, CCW have commented that customers have historically been uncertain about how long they would be without water and whether they would need to initiate coping strategies for hygiene and cleanliness, as well as drinking water (Ofwat & CCW, 2023). This is discussed more in section 10.

Supply restrictions

There is a lack of evidence regarding the impact of water restrictions on future customer expectations or customer satisfaction. The CCW Water Matters 2024 survey found that 26% of respondents had never had a problem with a water shortage, and that 19% of respondents had never experienced a hosepipe ban (CCW, 2024). CCW speculated that there is a bias in how customers perceive resilience, with those who have not yet experienced disruption assuming that the system is resilient while those who have considering it not to be. The selection bias should be carefully considered when using customer surveying and satisfaction techniques to assess customer expectations.

1.4.3 Burden of responsibility

As previously discussed, there is currently a disconnect between legal requirements for supply / adequate supply for domestic purposes and customer and regulatory expectations of sufficiency, and this disconnect is common internationally. Thus far this report has considered only supply, but demand should also be considered. The joint responsibility of ensuring there is sufficient water is well understood with stretching targets and requirements in place for developers, households, the non-household sector and water companies to increase water efficiency and decrease water consumption. The burden of responsibility should be considered here. For example, as water companies have commitments in their WRMPs and business plans to reduce demand it could be considered double jeopardy to punish companies for providing insufficient supply if this is as a result of failure to reduce demand. Similarly, for aspects such as non-household demand where the target is imposed on MOSL, it may be reasonable to assert that 'sufficient' supply might decrease in line with those targets.

It should also be considered whether the planning process is fit for purpose. Water companies currently do not have the right to reject a domestic connection and are not a statutory consultee for new developments[5,6] (see Section 45 of the WIA) (Burnett, et al., 2025). Indeed, it is implicitly assumed that it is the water company's duty to have or create sufficient capacity in their system to meet the current and future needs of all current and new connections.

Under Part G of the UK Building Regulations, new housing developments are required to determine the development's water efficiency to ensure it meets the minimum standard (125 l/p/d) (The Building Regulations, 2010). These calculations must be provided to the planning authority, but not the water company.

Limited consultation (or no consultation) during the planning process means that risks to water sufficiency and continuity may be poorly represented thereby giving limited visibility to water companies to plan and improve systemic resilience. It has also been repeatedly shown that non-technical factors like regulations, politics, and stakeholder concerns strongly impact the planning process (Water Research Foundation, 2018).

However, in October 2024 Ofwat issued its conclusions from its second consultation on the Environmental Incentives Common Framework (EICF) which requires water companies in England to offer at least one incentive for achieving water efficiency better that the 110 l/p/d level set out in the Building Regulations (Ofwat, 2024). Water companies are required to publish processes for paying incentives and encouraging compliance. This change has resulted in Developer Services teams in water companies asking for similar fittings information directly via their new connections application process.

With respect to non-domestic use, water companies do have the right to refuse a connection to the potable supply, but only in particular circumstances:

- it must put at risk its ability to meet 'any of the existing or probably future obligations'

- OR there must be a contravention of regulations 3, 4 or 5(1)(c) of the Water Fittings Regulations (in so far as they apply by virtue of regulation 2 of those Regulations) in relation to the water fittings used or to be used in connection with: (a) the supply of water to the premises to be supplied by the licensee; or (b) the use of water in those premises. (UK Government, 1991).

- OR 'incur unreasonable expenditure' AND there is EITHER

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[5] *On 8 January 2021 the Conservative government was asked about whether water companies would be made statutory consultees for medium and large scale planning applications. The government response (13 January 2021) said that the list of statutory consultees is under "constant review".*

[6] Schedule 4 of The Town and Country Planning (Development Management Procedure) (England) Order 2015 indicates that the water company is only a mandatory consultee for new developments which involve boring or extracting oil and natural gas from shale (The Town and Country Planning (Development Management Procedure) (England), 2015).

- no building on the land
- OR the supply to be made is for 'purposes other than domestic',

1.5 Societal expectations of resilience

Raw water availability

The 1976 drought highlighted the importance of water resource management in water supply resilience (Rodda & Marsh, 2011). From a regulatory perspective, it is expected that water undertakers plan their raw water resources adequately to meet demand (UK Government, 1991), but is acknowledged that this may not always be possible due to extreme weather events and so levels of service are established in each water undertaker's drought plan which set out the acceptable frequency to implement demand measures to preserve water resources and maintain system resilience. The levels of service may be used to identify which weather patterns, water resource availability and demand is considered 'business as usual' and which may be considered a drought event. The resilience of raw water systems is discussed further in section 6.

During CCW's 2024 *Water Matters* survey, 46% of customers in England and 67% in Wales felt like there was plenty of water available in their local area, with 71.2% (rolling average 2016-2023) stating they were confident that water would be available in the future. Some 59% of customers were of the belief that in the longer term their water supply would be available without restriction (no hosepipe bans), a decrease from 63% in 2022 (CCW, 2024).

Asset resilience

Evidence is lacking on customer expectations of asset resilience, probably because it is disconnected from the customer experience and therefore beyond most customers' awareness. However, 72% of Scottish Water customers indicated 'replacing ageing assets to protect the environment and maintain services' would justify "*a slight increase in charges*". Scottish Water interpreted this as "*customers are looking for service standards to be maintained in the long term […] customers stressed the need to invest in infrastructure to protect the standards they are accustomed to today*" (Scottish Water, 2021).

Supply interruptions

In the UK, providing an uninterrupted water supply is a key expectation of customers, both for personal and business use. A report for Southern Water found that the continuous supply of clean wholesome water was the top priority for customers (Southern Water, 2024). As such, customers expect to be notified a reasonable time ahead of any planned interruptions to supply, including start and end times (CCW, 2023).

Affinity Water suggested that the customer impact of an overrun of a planned interruption and a long unplanned interruption are different as overruns of planned interruptions are likely to be short and customers were able to plan for the interruption.

84% of customers surveyed by CCW were generally satisfied with the way that they were compensated following Beast from the East (Ofwat, 2018). However, the payments made by companies varied significantly:

- 12 to 24 hours interruption £20 to £75;
- 24 to 48 hours interruption £20 to £100;
- 48 to 72 hours interruption £30 to £150.

It was also noted that in some cases compensation was paid much quicker than the statutory limit of 20 working days, while others failed to comply with this limit. Some companies chose to pay above the statutory limit as they felt that '*customer acceptance of outages [was] lower than the standards prescribed*', as well as that minimum levels had not been index-linked. As such, in 2024 a consultation was published regarding the GSS and proposed to increase the payment values roughly in line with inflation, as well as some other changes to the standards that warranted payments. Some 82% of respondents supported the proposed increase, with 66% supporting the specific values proposed (Defra, 2024).

The importance of communication over actual network resilience was also repeated in US water sector findings. The JD Water Survey found that while "*one of the most negative effects on satisfaction is a service interruption caused by pipeline work. Satisfaction scores are 42 points lower among those experiencing pipeline work-related service interruptions than those among customers who experience no interruptions. However, when customers have previously been made aware of water utility system upgrades, satisfaction scores are 58 points higher among those who experience no service interruptions*" (J.D. Power, 2018).

CCW concluded that payments for failing to keep appointments, failing to provide notice of a planned supply interruption, and failing to restore supply should be increased above the rate of inflation as these had heightened degrees of perceived disruption (Defra, 2024).

Alternative supplies

Expectations of resilience are implicit in requirements for water companies to provide a continuous supply of wholesome water, however that may be achieved, including the use of non-piped alternative supplies. Where this is not achieved, the regulator expects water undertakers to pay customers on the priority service register £50 when they fail to provide the promised service or support (Defra, 2024).

Limitations of customer expectations

UKWIR pointed out some limitations of using customer engagement to communicate resilience issues (and hence understand customer expectations) (UKWIR, 2017). In particular they noted:

- Resilience measures often relate to low probability, high impact events. Customers are often not familiar with the concepts of risk and struggle to understand probabilities and percentages. In addition, research in behavioural economics has shown that people tend to overestimate the likelihood of small probabilities, giving them undue weight in decision making and overvaluing the benefit of further reducing a small probability. The result of this would be for perceived customer expectations to be for a higher level of resilience, and, having a higher willingness to pay for that level of service, than they would if they had full knowledge or experience of the issue.

- Due to the fact that supply failures occur relatively rarely, many customers won't have experience of the disruptions being discussed and will struggle to correctly understand the impact of the failure or possible mitigating measures / responses. This reduces the confidence that we can have in consumer studies on resilience and sufficiency.

- Investments in resilience are long-term and provide benefits that will impact future generations in addition to existing customers. Customers will generally underestimate this benefit, valuing their own welfare above those of future generations. Maintaining intergenerational fairness also impacts the ability to use willingness to pay as a metric for understanding expectations for levels of service as there would be a willingness to pay from all benefactors, not just current customers.

- Customer expectations are significantly impacted by context and the information provided to them. As such, expectations can change substantially as a result of awareness and attribution of blame.

1.6 Balancing customer expectations using willingness to pay

Customer service improvements come at a cost and care should be taken that water companies are not incentivised to spend money on increasing resilience in a way that is not in the public interest. In the case of a fair market this amounts to ensuring the impact of such expenditure on customer bills does not exceed the customer's willingness to pay for that improved level of service. In some instances, regulators may have to address an unwillingness of customers to pay for improvements that are in the public interest, but, as level of service and continuity of supply directly impact customer experience, it might be assumed that customer valuation provides a reasonable approximation to the real value of improvement measures (within the limitations of willingness to pay as a method of measuring social preference). The consideration of willingness to pay is largely out of scope of the current project but is mentioned here to identify the gap. Water companies typically undertake willingness to pay studies to inform their business plans. Relevant studies on this topic might include the following:

- Willis, K. G., R. Scarpa, and M. Acutt. 2005. "Assessing Water Company Customer Preferences and Willingness-to-Pay for Service Improvements: A Stated Choice Analysis." Water Resources Research 41: W02019.

- United Utilities Water. 2016. Improving Customer Research and Engagement. Warrington: United Utilities Water.

- Reid, S., A. Chalak, and J. Hecht. 2010. “Determining the Optimal Investment Plan for Water Utilities: the Case of Veolia Water Central.” Water Supply 10 (3): 367–375.

- Hensher, D., N. Shore, and K. Train. 2005. “Households’ Willingness-to-Pay for Water Service Attributes.” Environmental and Resource Economics 32: 509–531

In addition, UKWIR suggested that customer valuation of resilience could be assessed by the following methods (UKWIR, 2017):

- Revealed preference: data on retail sales may allow for study of customer behaviour during service disruption, such as the impact of disruption on the market for substitute goods such as bottled water. This could suggest a lower bound for their willingness to pay for avoiding service failure and suggest what quantity of supply they consider essential (or, if demand is assumed to be inelastic[7], sufficient).

- Use of customer service data such as contacts, complaints, and social media interactions to understand customer attitudes towards different types of service failure. The number, frequency and distribution of such interactions all provide information. Monetary value could be attributed by considering the cost of the time spent by customers contacting their water company to complain.

- Consideration of the economic impact of the service disruption. This might include lost income from businesses.

CCW found that customers were generally not aware of service standards and that they could be entitled to a payment in these standards are not met. The research also highlighted that the current standards do not align with customer expectations, citing that customers wanted additional standards to focus on water quality and the wider environment. Furthermore, they wanted more support for vulnerable individuals, although not all thought that this should come in the form of additional cash compensation (CCW, 2023).

[7] If demand for water is fairly constant, no matter what the price, then it is ‘inelastic’. Without evidence on the elasticity of water supply we cannot assert whether this is the case. Demand might be inelastic e.g. because it is considered to be very cheap relative to a consumer’s disposable income. In such a case then the quantity of water purchased by other means reflects the amount of water customers feel is sufficient (i.e. they bought all they wanted and wouldn’t have bought more even if it were cheaper). Of course, the direct cost is a poor estimator of value when it comes to a commodity like water as it is bulky, heavy, and people value convenience. That is, there may be no quantity of bottled water which would meet customer’s expectations as it is not practical to be used in the same way (e.g. heated).

2. The current UK regulatory landscape

2.1 Legal requirements

2.1.1 Resilience

The resilience objective was added to section 2 of the WIA by the Water Act 2014. The resilience objective is designed to secure the long-term resilience of water supply and sewerage systems and refers specifically to environmental pressures, population growth and changes in consumer behaviour. Ofwat are required to ensure that undertakers take action to make water and sewerage services to consumers resilient for the long term (UK Government, 2014):

> *(2DA) The resilience objective mentioned in subsection (2A)(e) is—*
>
> *to secure the long-term resilience of water undertakers' supply systems and sewerage undertakers' sewerage systems as regards environmental pressures, population growth and changes in consumer behaviour, and*
>
> *to secure that undertakers take steps for the purpose of enabling them to meet, in the long term, the need for the supply of water and the provision of sewerage services to consumers, including by promoting—*
>
> *i) appropriate long-term planning and investment by relevant undertakers, and the taking by them of a range of measures to manage water resources in sustainable ways, and to increase efficiency in the use of water and reduce demand for water so as to reduce pressure on water resources.*

The Water Act 2014 adds a new section 37AA to the WIA which can require that a plan be prepared on the basis of certain assumptions around resilience and security of supplies in drought and may be related to the risk of certain weather events arising, the frequency of customer restrictions or other bases for describing resilience, such as water security margins.

This provision applies only to water undertakers whose areas are wholly or mainly in England.

2.1.2 Sufficiency of supply

The Water Industry Act gives the Chief Inspector of Drinking Water powers and duties in relation to sufficiency of water supplied. They have powers to impose obligations on water undertakers. It notes that these may require undertakers to conform to prescribed standards or processes and to furnish prescribed persons with information required to carry out their functions.

Section 65 of the Act requires that "*water in such of its water mains and other pipes […] to be laid on constantly*".

2.1.3 Adequate pressure

Section 65 of the WIA requires water companies to provide supply to customers that has sufficient "*pressure as will cause the water to reach to the top of the top-most storey of every building within the undertaker's area*" or the height "*that to which it will flow by gravitation through its water mains from the service reservoir or tank from which that supply is taken*", whichever is least. This requirement does not apply "*during any period during which it is*

***reasonable** for that supply to be cut off or reduced for the purposes of the carrying out of any **necessary** works*".

2.1.4 Maintaining supply

Security and Emergency Measures (Water and Sewerage Undertakers and Water Supply Licensees) Direction, 2022

The *Security and Emergency Measures (Water and Sewerage Undertakers and Water Supply Licensees) Direction*, 2022 (SEMD), as explained by the *Keeling Schedule* (Defra, 2022), places additional obligations on water undertakers with regard to having plans in place to ensure continued exercise of its functions, having reasonable measures in place to mitigate risks to provision of its functions, and the requirement to provide water supply licensees with water when they are unable to provide supply to their customers in emergencies. Failure to meet these requirements would be deemed to be failing to provide sufficient supply.

In England and Wales, the Secretary of State and the Welsh Assembly Government have powers to "*issue Directions to undertakers in the interests of national security and/or mitigating the effects of a civil emergency*" (UK Government, n.d.).

SEMD22 states that:

(4) Plans for water supply must be prepared on the basis that the company must—

(a) continue to carry out—

(i) all of its water supply functions; or

(ii) where the nature of the civil emergency or security event is such that this is not possible, those functions which it can continue to exercise;

(b) in the event of an unavoidable failure of piped water supply, ensure that such minimum supply is provided by alternative means, as may be notified to the company by the appropriate authority

Water Industry Act 1991

When a water undertaker is carrying out necessary works (as defined by section 60(1) of the WIA[8] (UK Government, 1991)), the undertaker is required to issue "*reasonable notice*" "*except in an emergency or in the case of a reduction which is immaterial*". Furthermore,

[8] "*cut off a supply of water to any premises, if it is reasonable for the disconnection to be made, or the supply to be cut off, for the purposes of the carrying out of any necessary works. The power of a water undertaker under this section to cut off a supply of water shall include power to reduce a supply of water.*"

…it shall owe a duty to the consumer to secure—

(a) that those works are carried out with reasonable dispatch; and

(b) that any supply of water to those premises for domestic purposes is interrupted for more than twenty-four hours for the purposes of the carrying out of those works only if an emergency supply has been made available (whether or not in pipes) within a reasonable distance of the premises.

The Water Supply and Sewerage Services (Customer Service Standards) Regulations 2008

Under the circumstances described above by the WIA, section 8 of the regulations specifies the notice to customers must specify

(i) the earliest date and time after which the undertaker reasonably expects that the supply will be interrupted or cut off; and

(ii) the latest date and time by which the undertaker reasonably expects that the supply will be restored; and

(b) if the water is to be cut off for more than four hours, give at least 48 hours' notice before the supply is interrupted or cut off.

In addition, in cases of an "emergency" where the circumstances in the WIA do not apply,

…the undertaker must, as soon as is reasonably practicable, take all reasonable steps to notify each affected customer—

(a) that the supply has been interrupted or cut off;

(b) where an alternative supply can be obtained;

(c) of the time by which it is proposed the supply should be restored"

The required customer payments are also stipulated.

Section 9 of the regulations further stipulates that

…[t]he undertaker must restore the supply—

(a) by the time and date specified in the notice, if the undertaker has served a notice stating when the supply is to be restored;

(b) within 48 hours after it first became aware that the supply was interrupted or cut off, if the supply was interrupted or cut off in an emergency because of a leak or burst in a strategic main[9]*; or*

(c) within 12 hours after it first became aware that the supply was interrupted or cut off, if the supply was interrupted or cut off in an emergency, but not because of a leak or burst in a strategic main.

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9 "*a main that conveys water in bulk to centres of population that have no other supply that can fully meet normal demand*".

This does not apply in the case of drought. However, it notes that "*in a case [where] circumstances are so exceptional that it is unreasonable to expect the supply to be restored within the relevant period*" customers are not due payment. This suggests that **the current view of sufficiency is linked to resilience: the requirement is for water companies to restore supply within the permitted time period, but it is not deemed a customer service failure to fail to do so in extenuating circumstances**.

Section 10 then specifies minimum water pressure as *seven metres static head* and a customer service failure which requires customer payment as *two occasions lasting one hour or longer* in a 28-day period. This implies that, for example, pressures greater than seven metres static head and occasional periods (less than twice per 28 days) of low pressure (no matter how long they last, may be considered acceptable (UK Government, 2008).

2.2 Expectations set by Government

Keeping the Country Running (2011) is the current UK Government guidance on resilience. It considers resilience as the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event. It also sets out that there are different ways in which resilience provision can be delivered (Cabinet Office, 2011). These are categorised as:

- redundancy (avoiding dependencies on single assets);
- resistance (proofing the system so that it is resistant to known risks – for example, flood defences or access procedures);
- reliability (a system that operates effectively, irrespective of whether or not risks materialise – for example, design standards); and
- response/recovery (the ability to recover quickly so that service is not unduly impacted – that is, tested procedures and appropriate resources).

The main UK guidance on emergency preparedness is based on Part 1 of the Civil Contingencies Act 2004 (UK Government, 2004), which sets out duties and expectations for organisations involved in civil protection (Category 2 responders) (DWI, 2022).

The Welsh Government's strategic policy statement sets a resilience objective for short-term and long-term challenges which includes ensuring that water company "*assets and services are resilient against, for example, natural hazards, asset failure and other threats including cyber security*" (Ofwat, 2019)., while their *strategic priorities and objectives statement to Ofwat* states that they should *"challenge companies to monitor their asset health and provide forward-looking plans to address any issues over the long-term [so that companies] demonstrate a clear understanding of the health of their existing assets including interdependencies, trends in the long-term, and how this impacts levels of overall resilience"* (Welsh Government, 2022).

The UK Government's strategic priorities for Ofwat are similar, including the requirement to *"promote good asset management and challenge companies to better understand the health of their assets and adopt a strategic and long-term approach"* (Defra, 2022)

In addition, the National Audit Office recently reported on the performance of Defra, Ofwat, Environment Agency and DWI. They noted that performance in "*key measures, including mains bursts, supply interruptions and pollution incidents*" had been stagnant for the last 10 years and concluded that "*[t]he Department for Environment, Food and Rural Affairs (Defra) and water regulators have failed to drive necessary investment for the sector, which now faces significant environmental, supply and infrastructure challenges*" (National Audit Office, 2025). This suggests that Ofwat failed sufficiently to incentivise improvements in resilience.

2.2.1 Findings of the interim report of the Water Industry Review

This project is contemporaneous with the Sir John Cunliffe Water Industry Review. In agreement with NIC, the interim report criticises the lagging measures of asset health and maintenance expenditure used by Ofwat and the lack of standards (Independent Water Commission, 2025). This is contrasted to the forward looking approach which has been taken by Water Industry Commission for Scotland, driving higher mains replacement rates (section 2.7).

The Commission's current view is that there is a strong case for a single, comprehensive infrastructure resilience framework across all water companies in England and Wales, which includes (i) establishment of resilience standards, (ii) a requirement for water companies to gather and report data on their assets and (iii) a more supervisory role for the regulator to enable a better understanding of an individual company's assets and more tailored regulation, including in the setting of allowances and performance targets.

Resilience standards should ensure all companies make forward-looking, long-term assessments of asset health and of their ability to recover from disruption to critical infrastructure. They should be outcome focused, rather than focused solely on how long an asset should last, so where assets have back-up or redundancy, that can be factored into the assessment. The framework could also provide guidance for how companies could meet resilience standards without stipulating a particular course of action, to allow companies to identify the most efficient approach

Standards would help to reduce the risk of failures leading to service disruptions and help increase resilience for the ongoing operation of assets.240 The Commission further understands that there could be benefit in specifying outcome-based resilience standards at the system level, rather than prescriptive requirements for individual assets. This would provide flexibility for the different conditions that companies operate in, such as geographic and climatic, while ensuring the sector reaches a consistent level of resilience.

To support such a framework, the Commission is also considering whether new requirements are necessary on companies to gather and assess asset condition and report them, at set intervals, to the regulator. This would fill gaps in the existing approach. For example, there are currently limited exemptions to asset mapping requirements where the undertaker is not aware of the existence of a sewer main or if discovering the main is not 'reasonably practicable

2.3 Expectations set by DWI

The DWI website provides advice relating to supply interruptions which provides an accessible summary of customers' rights under GSS.

In response to the Beast from the East weather event in 2018 the DWI also noted the risk associated with reliance on water transfers as these supplies were unavailable in times of shortage as the supplying companies needed to meet their own supply needs. The DWI reiterated that "*Regulation 27 in England and Regulation 28 in Wales of the Regulations requires companies to have in place risk assessments for all their supply systems to establish whether there is a significant risk of supplying water that could constitute a potential danger to human health or is likely to be unwholesome*" and recommended that water companies review their contingency plans and bulk supply contracts to ensure that sources will be available when they are needed (DWI, 2018).

2.4 Expectations set by Environment Agency

The Environment Agency notes that while the SEMD requires that customers receive 10 litres/day of potable water per day at all times, "*[c]ustomers generally use around 150 litres/head/day and therefore a reduction of this magnitude for any long period of time is likely to be considered unacceptable*".

A significant proportion of expectations in water supply resilience and sufficiency are based on WRMP expectations. As the environmental regulator, the Environment Agency expects company WRMPs to consider changing legislation, urban and economic growth, and future abstraction licence limitations. The Environment Agency expects companies go to beyond mandated environmental considerations to ensure a resilient and sufficient water supply while also allowing for a resilient environment with sufficient water to meet legislative targets. This includes that environmental benefits are considered during water resources management option selection and development. In addition, the Environment Agency expects to see water companies driving down the demand for water, including reducing leakage, and identifying innovative new sources to reduce the pressures on the natural environment (Environment Agency, 2024).

There is an increasing expectation to include water quality within water resource planning and to collaborate with other sectors to develop options that have multiple benefits, looking at water planning holistically (Environment Agency, 2024). Cross-sector collaboration is expected through regional planning groups. A water company is expected to work closely with their regional group (Environment Agency, 2020). The regional plans are expected to (Environment Agency, 2024):

- support growth and access to water in their region, across sectors
- consider the benefits of proposed supply side options to water users, other than public water supply

- set out what further evidence and work may be required to do this more effectively in the future
- take a catchment-based approach and consider catchment-based work to improve water management.

2.5 Expectations set by Ofwat

Ofwat stated that outcomes for customers must be clearly laid out in water company business plans, including resilience of supply, the risks to outcome delivery, and evidence of consideration of options to mitigate said risks. They went on to highlight that they were "*keen to see [consideration of] whether optimal solutions can be found through taking a strategic, regional, view across company boundaries, across sectors and considering third party options, alongside demand side measures, tackling leakage and water efficiency*" (Ofwat, 2015).

2.5.1 Furthering the resilience objective

Ofwat considers it its general duty under section 27 of the Water Industry Act 1991 to keep "*under review the way in which companies carry out their functions and primary duties to further the consumer objective to protect the interests of consumers and the resilience objective to secure the long-term resilience of water companies' water supply and wastewater systems*" (Ofwat, 2015).

In particular, they consider it to be their responsibility to ensure that wholesome water is "*available all the time*" and that customers receive "*proactive messaging if there must be an interruption*".

They also recognise the need to "promote *long-term planning and investment, and the use of a range of measures to manage water resources in sustainable ways; and increase efficiency in water use and reduce demand for water to minimise pressure on water resources*" (Ofwat, 2015).

Ofwat also set out their expectations on water companies, stating that they expect water companies to "*anticipate trends and variability in order to maintain services for people and protect the natural environment, now and in the future*" and that critical infrastructure should be protected (Ofwat, 2019).

2.5.2 Continuity of supply

Water companies are required to maintain a priority service register (PSR). The PSR contains vulnerable customers who require additional support/provision during emergencies, such as additional alternative supplies during supply interruptions and priority contact during emergencies/supply interruptions (Ofwat, n.d.).

Ofwat state that water-critical businesses require weeks, if not months, notice for planned supply interruptions and that there is an expectation of appropriate fresh-water provision for drinking and washing when supply fails, as well as fixing the supply issue quickly.

The National Guidelines for Firefighting state that (Water UK, 2007):

"*(1) A person who proposes to carry out works for the purpose of supplying water to any part of the area of a fire and rescue authority must give at least 6 weeks' notice in writing to the authority.*

(2) A person who proposes to carry out works affecting a fire hydrant must give at least 7 days' notice in writing to the fire and rescue authority in whose area the hydrant is situated.

(3) If it is not practicable for a person to give notice as required by subsection (1) or (2), he is to be regarded as having given the notice required by that subsection if he gives notice as soon as practicable."

2.5.3 Customer-focussed license condition

Ofwat recently (February 2024) introduced a customer service aspect to the licence of each company in England and Wales, the 'customer-focused licence condition', found in Condition G of each licence (Ofwat, 2025). The license condition for English companies is provided for reference in this document in Appendix D.

This condition lists the following 'principles of customer care' which companies must meet:

- Customers are well-informed:
- When something does go wrong, affected customers have confidence their company will put it right
- The full diversity of customers' needs is identified, understood and met by companies in the services and extra help they provide

Consulting on the new condition, Ofwat found that "*[t]he Outcomes and Principles represented what all participants felt water companies should be doing as a basic function of their customer service operations. While some considered them insufficiently detailed on their own, they were reassured with the accompanying guidance*" (Walnut Unlimited , 2023).

Further details can be found in the accompanying guidance (Ofwat, 2025).

Planning

As stated in Section 2.5, Ofwat stated that outcomes for customers must be clearly laid out in water company business plans, including resilience of supply, the risks to outcome delivery, and evidence of consideration of options to mitigate said risks. They highlighted that they were interested to see consideration of whether optimal solutions could be achieved "*through taking a strategic, regional, view across company boundaries, across sectors and considering third party options, alongside demand side measures, tackling leakage and water efficiency*." This includes showing consideration for the supply needs of customers now and in the future through public consultation and assurance from the Board that said plan "*represents the most cost effective and sustainable long-term solution*" (Ofwat, 2015).

Environment

As economic regulator, Ofwat has a role in incentivising water companies to meet environmental obligations efficiently, to understand the environmental outcomes that customers want, and to understand the risk to the environment's ability to support water company services and how they can assist in mitigating them (Ofwat, 2015).

With respect to the Beast from the East event, Ofwat concluded that the customer impact experienced largely depended on factors that were within a water company's control, such as water company's plans for handling major incidents (Ofwat, 2018).

2.5.4 Resilience in the round

'Resilience in the round' was introduced in the 2019 price review following advice and findings from an independent Task and Finish Group and related consultation. Ofwat describes it as "*what matters to customers and is a core concept […] in order to manage resilience in this more complex and less predictable world, companies will need to see the bigger picture if they are to deliver against customer expectations – linking corporate, financial and operational elements together with customers at the heart*" (Ofwat, 2017). Ofwat defines:

- **Corporate resilience** is the ability of a water company's governance, accountability and assurance processes to help avoid, cope with and recover from, disruption of all types, as well as to anticipate trends and variability in business operations.
- **Financial resilience** is a water company's ability to avoid, cope with and recover from disruption to its finances.
- **Operational resilience** is the ability of infrastructure, and the skilled employees that operate said infrastructure, to avoid, cope with and recover from, disruption in its performance.

Ofwat stated in their 'Resilience in the round' report that meaningful methods to measure and monitor resilience are an important factor in achieving long-term resilience. The resultant metrics will need to be forward looking and focused on what matters to customers but that resilience metrics are difficult to develop as they relate to threats that have either rarely or never materialised, or are currently unidentified (Ofwat, 2017).

In justifying the need for 'resilience in the round', Ofwat noted that whilst system maturity had been assessed by some companies in relation to resilience, it was rarely used to inform action plans. Similarly, whilst maturity targets were also set by some companies, they were typically short-term and it was unclear whether there were tangible measures and proposals to deliver them. They also noted that companies had generally considered a variety of hazards within their resilience frameworks, (see Appendix G), however there was a lack of systems-based approach to resilience meaning that these considerations were of little value when informing 'in the round' assessments of risks. Furthermore, they facilitated limited synergies between operational, financial and corporate aspects of resilience (Ofwat, 2017).

Ofwat stated that companies needed to (Ofwat, 2019):

- Continue engaging with customers on resilience and future expectations.
- Review and implement resilience best practices across the organisation, including developing a resilience framework.
- Regularly review and enhance resilience action plans, ensuring ongoing delivery monitoring.
- Collaborate to strengthen regional and national operational resilience and asset health, considering climate change and population growth.

In response, a United Utilities report (Arcadis, 2017) on measuring resilience in the water industry also recommended that resilience metrics should:

- be at a level of detail appropriate to the scale of the risk (i.e. measurement of resilience to material risks)
- be practical to measure
- measure impacts on customers and the environment, and
- establish the minimum levels of resilience expected.

2.5.5 Ofwat proposals for improving asset management maturity

Ofwat recently published an update on its PR24 aim to improve sector-wide understanding of asset health for priority assets (Ofwat, 2025) and a consultation on a proposal to replace Condition L in water company licenses with a new condition relating to asset management maturity. These documents acknowledge the lack of understanding by the regulator of asset condition, asset health and proactive asset management and propose the mandating of ISO 55001 certification as a minimum common level of asset management maturity. They further propose annual self-assessment by companies of their maturity using the IAM's self assessment methodology tool (SAM+) which Ofwat would use to inform their own sector-wide asset management maturity assessment. Ofwat are also developing metrics to *"to evidence the effectiveness of the asset management framework and information sharing to identify/promote best practice"* (Ofwat, 2025).

2.6 Expectations of National Infrastructure Commission

The NIC's 2024 report *'Developing resilience standards in UK infrastructure*' was catalytic in the commissioning of this work. As such, a critical appraisal of the report is included in Appendix A. The report recommends the creation of a set of resilience standards "*by 2025 so that around £400 billion of investment decisions due in the next five years can factor in these targets that citizens can expect from key infrastructure services, such as the service levels available in different scenarios and the speed of recovery from major incidents*". (National Infrastructure Commission, 2024).

Water UK in their response to the Call for Evidence for the Water Industry Review echoed the recommendations, asking for outcome-based standards for resilience which are enforceable by law (Water UK, 2025) while the interim report claims that *"water and sewerage companies were supportive of the proposal to introduce resilience standards. There was broad support for the proposals set out by the NIC, with one arguing that it should be considered a key priority"*.

2.7 Regulatory and government expectations in other parts of the UK

Citizens Advice Scotland state that for planned interruptions of 4 hours or more, Scottish Water customers should be given at least 48 hours' notice. This may be in the form of a letter or a "*news item in the press or on TV*". For unplanned interruptions, Scottish Water must provide an alternative supply if the water is off for 12 hours or more. Scottish Water is required to pay compensation if it fails to provide notice for a supply interruption, although it does not have to be paid automatically (Citizen Advice Scotland, n.d.).

3. International legislative approaches to resilience and sufficiency

3.1 Australasia

3.1.1 Australia

Infrastructure Australia state that to address long-term water security challenges and risks, a nationally consistent framework is essential which should include a method to assess water security over time, integrating demographic, scientific, and economic data to identify deficits or surpluses, business case development for state, territory, and a national infrastructure framework (Infrastructure Australia, 2021).

Service standards

New South Wales

Sydney Water's minimum service commitment is to maintain ≥15 m head pressure at all connection points to both residential and non-residential customers and water restrictions should not occur more than once every 10 years. When they do occur, they should "*last no longer than 3% of the time*" but the interpretation of this is not clear. WaterNSW design guidance also claims that *storages should not approach emptiness (defined as 5% of water in the storage) more often than 0.001% of the time, or one chance in 100,000 in any one month* (WaterNSW, 2025; Metropolitan Water Directorate, 2017).

Queensland

Under the *Water Act 2000*, regulations may define Level of Service (LOS) objectives for water security. In the South East Queensland region these objectives establish targets for water restriction duration, frequency, and severity to ensure long-term supply reliability for communities, businesses, and industries. Exclusions are made for short-term disruptions (e.g., floods, bushfires, vandalism) and operational issues (e.g., power failures, leaks, metering inaccuracies), as these are addressed separately under state frameworks. The *Water Supply (Safety and Reliability) Act 2008* mandates annual performance reporting by Water Service Providers (WSPs) (Department Natural Resources, Mines and Energy, 2018).

Victoria

The *Victoria Urban Water Industry Standard* states that water businesses must meet defined service standards that specify minimum performance levels for customers. These are summarised in Table 3.1 (Essential Services Commission, 2024).

Minimum flow rate requirements may not apply in cases of (Essential Services Commission, 2024):

- Substandard property infrastructure
- Private extension services
- Drought or emergency conditions
- Peak summer demand shortages
- Planned/unplanned interruptions
- Reduced recycled water supply (due to shortages or permitted use rules)
- Regulatory restrictions under the *Water Industry Standard, Water Act 1989 (s145)*, or *Water Industry Act 1994* (Vic).

Table 3.1 2024-25 levels of service – Water Industry Standard-Urban Customer Service

Water Company	Minimum water pressure or flow rate a customer should receive (l/min)	Minimum water pressure a customer should receive (m head)	Maximum number of unplanned water supply interruptions a customer should experience in any 12-month period	Number of customers experiencing >5 unplanned water supply interruptions in the year	Average time taken to attend bursts and leaks (priority 1) (minutes)	Average time taken to attend bursts and leaks (priority 2) (minutes)	Average time taken to attend bursts and leaks (priority 3) (minutes)	Average duration of unplanned water supply interruptions (minutes)	Average duration of planned water supply interruptions (minutes)
Coliban Water	20	-	5	-	35	35	71	75	145
East Gippsland Water	20	-	5	-	35	35	71	75	145
Gippsland Water	-	14	5	-	35	90	1500	90	150
Goulburn Valley Water	20	-	4	-	60	60	160	120	120
Greater Western Water	20*	-	5	-	30	90	315	150	20
GWM Water	20	-	5	-	30	40	40	100	200
Lower Murray Water	20*	-	5	-	20	20	20	60	85
North East Water	-	-	-	375	30	30	240	100	95
South East Water	20	-	5	-	36	92	317	88	179
South Gippsland Water	20*	-	5	-	30	35	500	110	240
Wannon Water	20*	-	5	-	22	24	51	138	149
Westernport Water	-	30	4	-	30	35	300	85	157
Yarra Valley Water	20*		2	-	24	36	286	113	101

*Varies by diameter - 20 for a 20 mm diameter connection

Tasmania

Table 3.2 shows Tasmania's proposed level of service objectives. The implementation timeline for this is 20-30% compliance by 2030, 50-60% compliance by 2040 and 100% by 2050.

Table 3.2 Proposed level of service objectives for water security (TasWater, 2023)

Description	Proposed level of service
Water restriction frequency	No more than once in 10 years on average (10% annual probability)
Water restriction duration	No more than six months of restrictions in 10 years on average (5% annual probability)
Critical minimum per capita water volumes (residential/commercial	100 litres/person/day
Minimum supply for essential industrial customers	Varies by system

Northern Territory

Under the *Water Supply and Sewerage Act 2000*, the Minister may establish minimum service standards for licensees, covering (Water Supply and Sewage Services Act, 2000):

- Water quality
- Supply standards (pressure, flow)
- Service reliability

These standards must:

- Match pre-existing service levels
- Align with national benchmarks
- Consider local delivery costs

Risks

Victoria

The *Safe Drinking Water Act 2003* mandates that water companies (Safe Drinking Water Act, 2003):

- Prepare, implement, and continuously review risk management plans for drinking water supply
- Update plans as needed based on review findings.

Supply

The *Water Act 2007* states that critical human water requirements need to be taken into consideration when developing a basin plan. Critical human water needs take priority and are defined as "*the needs for a minimum amount of water […] required to meet* (Parliament of Australia, 2007)*:*

(a) core human consumption requirements in urban and rural areas; and

(b) those non-human consumption requirements that a failure to meet would cause prohibitively high social, economic or national security costs."

The act further states that basin plans must include 'trigger points' where river water quality and salinity are unsuitable for meeting human needs (Parliament of Australia, 2007).

Queensland

The *Water Regulations 2016* establish stringent reliability standards for major water storage infrastructure, including the requirement that key dams will not fall below minimum operating levels more than once per 10,000 years on average (Water Regulation, 2016).

Equipment

The *Australian Drinking Water Guidelines* require that (Australian Drinking Water Guidelines, 2011):

- Equipment and infrastructure must be appropriately sized to manage all flow conditions (including peak demand).
- Systems must maintain adequate detention times and capacity.

Distribution

New South Wales

Sydney Water must ensure that ≥99.99% of properties experience fewer than 12 pressure failures annually, where pressure failure is defined as continuous pressure below 15 m head for ≥1 hour at connection point (Sydney Water, 2024). The flowing exemptions apply:

- Planned/unplanned water interruptions
- Firefighting or abnormal demand situations
- Temporary operational issues (e.g., main breaks) resolved within 4 days

Tasmania

Tasmania measures resilience through mains breaks, water supply interruptions and dam risk assessments (Tasmanian Economic Regulator, 2024).

New South Wales

Sydney Water's operating licence states that ≥98% of properties must remain unaffected by unplanned water interruptions each financial year, as per its water continuity standard. An interruption is considered unplanned if water at the first cold tap is interrupted, takes over 5 continuous hours for normal supply to be restored, and the occupant does not receive notice from Sydney Water 2 days prior to interruption if residential customer or 7 days if non-residential customer. Incidents caused by third party actions or power failures are exempt from this definition (Sydney Water, 2024).

The operating licence also requires Syndey Water to maintain monitoring systems and processes to detect unplanned interruptions, pressure failures, and wastewater overflows using customer/community reports, pressure monitoring and Sydney Water's data collection system.

Sydney Water's operating licence defines a planned Interruption as a pre-notified event (residential: ≥2 days; non-residential: ≥7 days) which ceases when normal supply returns to the property.

The above obligations may be suspended during a 'force majeure' (event beyond reasonable control), which includes (Sydney Water, 2024):

- Severe weather (as classified by Bureau of Meteorology (BoM))
- Natural disasters (fires, floods, earthquakes)

Queensland

The Water Regulations 2016 stipulate that:

> *The bulk water supply system is to be able to supply enough water to meet the projected regional average urban demand.*
>
> *(2) The bulk water supply authority must—*
>
> *(a) work out the projected regional average urban demand in collaboration with the SEQ service providers, and publicly publish the projection in the way stated in the SEQ water security program; and*
>
> *(b) assess annually whether the projected regional average urban demand or latest projected regional average urban demand is still current, and publicly publish the outcome of the assessment in the way stated in the SEQ water security program.*

Where the projected regional average urban demand is the demand for each person for each day, for both residential and non-residential water use within the SEQ region for each year over the next 30 years. This is to ensure sustainable and secure water supply and demand management within the South East Queensland region (Water Regulation, 2016).

Water providers must have a water security programme to facilitate meeting the water security LOS objectives. A water security programme must include information on arrangements, strategies and measures for operating assets, future infrastructure needs, managing infrastructure, managing water demand, and responding to droughts (Water Regulation, 2016).

Western

The Water Services Act 2012 states that Licensees may interrupt water services for emergencies, maintenance, or repairs, provided they take reasonable steps to minimise disruption duration/impact. Licensees are not liable for any loss or damage caused by a supply interruption unless it was due to licensee negligence, actions made in bad faith, the licensee has agreed otherwise (Western Australian Legislation, 2012).

Victoria

The Water Act 1989 states that water authorities may reduce or disconnect supply due to, amongst others, water shortages or system capacity issues (Victorian Legislation, 1989).

The Northern Region Sustainable Water Strategy states that

> *…a water business must ensure that a customer's water supply and recycled water supply is at least equal to the water business' specified minimum supply pressure or flow rate, except to the extent that:*
>
> *(a) a property owner's infrastructure falls short of the required condition;*
>
> *(b) a service is provided via a private extension;*
>
> *(c) there is a drought or an emergency;*
>
> *(d) there is a water shortage due to peak summer demand;*
>
> *(e) there is an unplanned or planned interruption;*
>
> *(f) recycled water is reduced due to a shortage;*
>
> *(g) recycled water is reduced in accordance with a water business's permitted use rules;*
>
> *(h) supply is restricted or disconnected in accordance with this industry standard; or*
>
> *(i) the Water Act 1989 (Vic) and the Water Industry Act 1994 (Vic) provides.*

It is stipulated that restrictions should be in place only 5-10% of the time (Northern Region Sustainable Water Strategy, 2009).

South Australia

The Water Retail Code states that "*a retailer must use its best endeavours to minimise interruptions or limitations to supply and to restore supply as soon as practicable following an interruption or limitation to supply.*" The water retailers must have and adhere to policies which minimise the impact of planned and unplanned interruptions (Essential Services Commission of South Australia, 2024).

The Water Industry Act 2012 stipulates that the State Water Demand and Supply Statement must evaluate current water resources and available supplies, analyse present and projected water demand, and detail policies ensuring secure, reliable supplies to support economic growth. During events where there is insufficient water quantity/quality or infrastructure capacity limitations, water supplies may (South Australia Legislation, 2012):

- Reduce water supply through infrastructure
- Restrict/prohibit specific water uses or methods
- Implement time-based usage limitations
- Discontinue supply temporarily

Northern Territory

The Water Supply and Sewerage Act 2000 states that there is no requirement to connect or supply services when:

- Emergencies occur or preventative work is needed
- Circumstances beyond licensee's control arise
- Hazardous connections persist after disconnection
- Work is performed with reasonable notice/restoration
- Authorised by Act or Regulations

Furthermore, licensees may disconnect services without liability to avert danger, and Ministers may impose territory-wide water/sewerage restrictions via public notice (Water Supply and Sewage Services Act, 2000).

Cyber security

The Australian Cyber and Infrastructure Security Centre state that "*the Australian Government takes an all-hazards approach to resilience. It seeks to increase the capability of organisations and communities to survive, recover and adapt to all types of threats. This approach uplifts the security and resilience of critical infrastructure, in line with the Security of Critical Infrastructure Act 2018*" (Australian Government, 2024).

New South Wales

Sydney Water's operating licence states that it must maintain a cyber security management system, which must cover all IT infrastructure (hardware, software, networks) and operational technology systems and equipment (Sydney Water, 2024).

3.1.2 New Zealand

The *New Zealand Water Services Act (2021)* states that a drinking water supplier must provide 'a sufficient quantity of drinking water' to each customer. Sufficient is defined as "*the quantity of drinking water that is sufficient to support the ordinary drinking water and sanitary needs of consumers*", unless compliance rules have prescribed what a sufficient quantity is or provided a formula for determining a sufficient quantity (New Zealand Legislation, 2021).

Supply may be restricted in the event of maintenance, upgrades or repairs to the supply network; risks to public health; environmental factors affecting a water source; an emergency; or for cultural reasons. Planned and unplanned restrictions must not exceed 8 hours, unless the supplier has obtained approval or complies with a compliance rule for restrictions lasting longer than 8 hours and takes practicable steps to advise affected consumers of the restriction/interruption. Where restrictions last longer than 8 hours, water supplies must ensure that a "*sufficient quantity of drinking water is available to affected consumers through an alternative supply*" (New Zealand Legislation, 2021).

Where there is imminent risk to water supply sufficiency, companies must notify the water regulator (Taumata Arowai), Fire and Emergency New Zealand, and the local authorities in the affected area, as well as any other drinking water suppliers the affected drinking water supplier supplies. The supplier must also request that at least one of the local authorities exercise their powers to enable the supplier to continue to provide a sufficient quantity of water (New Zealand Legislation, 2021).

The *Local Government Water Services Bill* states that the objective of a drinking water supplier is to provide water services that […] "*are resilient to external factors (such as climate change and natural hazards)*" (Department of Internal Affairs Te Tari Taiwhenua, 2025). Regarding planning, the *Local Government (Water Services Preliminary Arrangements) Act 2024* states that a water services delivery plan must cover at least 10 consecutive financial years, and may include an additional 20 years if the information relates to investment requirements for water service infrastructure or support future urban development or housing growth (Local Government (Water Services Preliminary Arrangements) Act, 2024).

The *Wellington Water Regional Standard for Water Services* states that some customers (such as hospitals) may require a secure supply to reduce the risk of water outages due to maintenance activities. Such secure water supply connections may be from (Wellington Water, 2024):

- Dual connections to the same main, separated by a line valve and a minimum horizontal separation of 1 m, unless the connections have lateral restraint (flanged or welded connections), in which case they can be laid closer together. Both lines will require backflow prevention.

- Connections to two separate individual principal mains, both with backflow prevention.

The *Local Government (Water Services) Bill* states that the water supply network shall (Local Government (Water Services) Bill, 2024):

- Be designed and constructed with a nominal structural and operational life of 100 years. It should be built in a way that minimises its overall life-cycle costs.

- Be designed to accommodate the predicted hydrological impacts of climate change and sea level rise.

- Be designed using an adaptive pathways planning approach.

- Take account of the predicted flooding effects and any future upgrades that may be required.

- Have adequate standby pumping (100% pumping capacity) and emergency provisions to mitigate pump or power failure.

It also mandates the following levels of service storage volumes, as seen in Table 3.3.

Table 3.3 Mandated levels of service for storage volumes (Local Government (Water Services) Bill, 2024)

<table>
<tr><th>Storage (litres per person)</th><th>Scenario</th></tr>
<tr><td>700</td><td>Where actual consumption is not known such as new developments.</td></tr>
<tr><td>2 x average day demand, or</td><td rowspan="2">Used when demand statistics are available from Wellington Water.</td></tr>
<tr><td>Maximum day demand + 20% + SNZ PAS 4509 firefighting requirements (Standards New Zealand, 2008)</td></tr>
<tr><td>(20 litres per person per day for 23 days + critical users allowance) x 1.43</td><td>Water to determine critical users and their consumption.</td></tr>
</table>

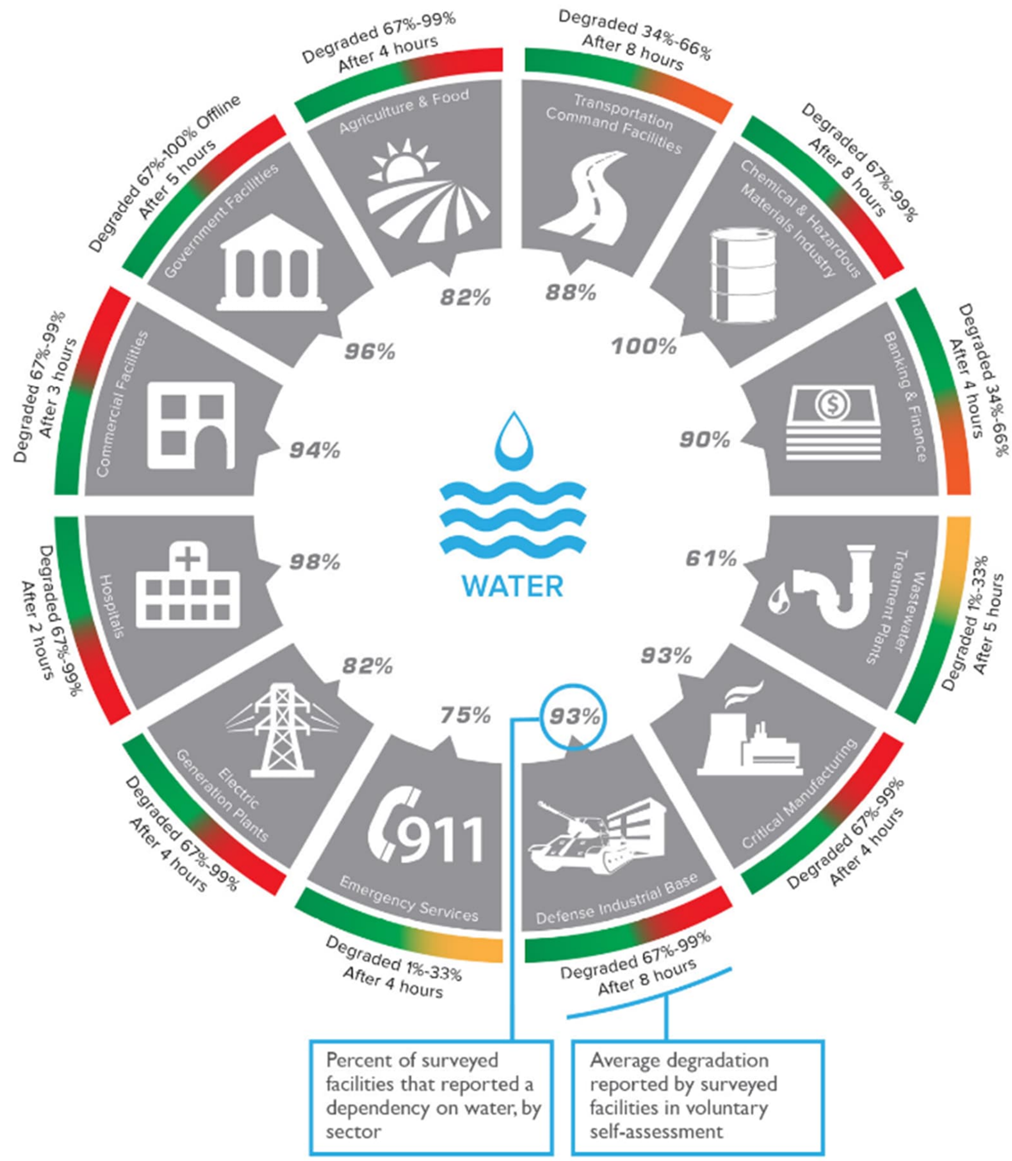
Gravity water supply pipelines supplying water to a reservoir should have sufficient hydraulic capacity to supply the volume of water used on the forecast peak day (excluding fire demand or pipeline failure) within a 24-hour period and maintain reservoir volume at or above 70% full under normal (excluding fire demand or pipeline failure) operating conditions (Local Government (Water Services) Bill, 2024).

3.2 North America

3.2.1 USA

The National Infrastructure Advisory Council (NIAC) undertook a study of the resilience of the US water sector in which it assessed security and resilience within the sector, identified key water resilience issues, and identified potential opportunities to address these issues. The study highlighted the sectors reliant on water supply and the associated impact after a certain amount of time (Figure 3.1) (National Infrastructure Advisory Council, 2016).

Figure 3.1 US sectors reliant on water supply and the associated impact of supply interruptions (National Infrastructure Advisory Council, 2016)



This study was the only research identified which sought to understand the criticality of non-domestic consumers and understand what might be considered to be an ‘acceptable’ length of outage. It suggests that 3-4 hours, with the exception of hospitals which would already be treated as a priority service, may be a suitable threshold to define an unacceptable length of supply outage.

Progress towards a resilient water sector in USA

The *US EPA Roadmap to a Secure and Resilient Water and Wastewater Sector* states that:

> *…the history of major disruptions show that water and wastewater services are receiving inadequate attention in disaster planning, prevention, and response among public officials and interdependent sectors. […] Resilience has not been substantially integrated into the actions of Federal agencies and resilient outcomes are not typically part of Federal programs and resources. In contrast to the Energy and Transportation Sector, the Water Sector does not have a cabinet-level department and there is no dedicated Emergency Support Function (ESF) for water (Water and Wastewater Sector Strategic Roadmap Work Group, 2024).*

However, the AWWA has developed the standard J100-10 (R13), which is the first voluntary standard encompassing an all-hazards risk and resilience management process specifically for water and wastewater utilities. Similarly, following the 2008 Roadmap to Secure Control Systems in the Water Sector, the AWWA developed a cybersecurity resource which provides the foundation for adopting the NIST Cybersecurity Framework (American Water Works Association, 2016).

The US EPA identified four critical components/core elements of resilience for which they set basic and advanced benchmarks which are optional to implement (Water and Wastewater Sector Strategic Roadmap Work Group, 2024):

- Risk assessments to outline risks and what assets are at risk
- Emergency response planning
- Training and exercises
- Recovery.

Other components which they consider as relevant to resilience include (Water and Wastewater Sector Strategic Roadmap Work Group, 2024):

- Having an emergency resource plan, including backup power and supplemental employees to operate facilities in an emergency.
- Establishing multiday water storage capabilities
- Finding mutual aid and assistance

Furthermore, the *US EPA 2015 Strategic Sustainability Performance Plan* provides the following goals and objectives for water sector resilience (Table 3.4).

Table 3.4 US EPA water sector goals and objectives (National Infrastructure Advisory Council, 2016)

Goal 1: Sustain protection of public health and the environment. The Nation relies on sustained availability of safe drinking water and on treatment of wastewater to maintain public health and environmental protection. To protect public and environmental health better, the Water Sector works to ensure the continuity of both drinking water and wastewater services.	
Objective 1	Encourage integration of both physical and cybersecurity concepts into daily business operations at utilities to foster a security culture.
Objective 2	Evaluate and develop surveillance, monitoring, warning, and response capabilities to recognize and address all-hazards risks at water systems that affect public health and economic viability.
Objective 3	Develop a nationwide laboratory network for water quality protection that integrates Federal and State laboratory resources and uses standardized diagnostic protocols and procedures, or develop a supporting laboratory network capable of analysing threats to water quality.
Goal 2. Recognize and reduce risk. With an improved understanding of the vulnerabilities, threats, and consequences, owners and operators of utilities can continue to thoroughly examine and implement risk-based approaches to protect, detect, respond to, and recover from all hazards better.	
Objective 1	Improve identification of vulnerabilities based on knowledge and best available information, with the intent of increasing the sector's overall protection posture.
Objective 2	Improve identification of potential threats through knowledge base and communications—with the intent of increasing overall protection posture of the sector.
Objective 3	Identify and refine public health and economic impact consequences of manmade or natural incidents to improve utility risk assessments and enhance the sector's overall protection posture.
Goal 3. Maintain a resilient infrastructure. The Water Sector will investigate how to optimize continuity of operations to ensure the economic vitality of communities and the utilities that serve them. Response and recovery from an incident in the sector will be crucial to maintaining public health and confidence.	
Objective 1	Emphasise continuity of drinking water and wastewater services as it pertains to utility emergency preparedness, response, and recovery planning.
Objective 2	Explore and expand implementation of mutual aid agreements/compacts in the Water Sector by encouraging utilities to join their State WARN. The sector has significantly enhanced its resilience through agreements among

	utilities and States; increasing the number and scope of these will further enhance resilience.
Objective 3	Identify and implement key response and recovery strategies. Response and recovery from an incident in the sector will be crucial to maintaining public health and confidence.
Objective 4	Increase understanding of how the Sector is interdependent with other critical infrastructure sectors. Sectors such as Healthcare and Public Health and Emergency Services are largely dependent on the Water Sector for their continuity of operations, while the Water Sector is dependent on sectors such as Chemical or Energy for continuity of its operations.
Goal 4. Increase communication, outreach, and public confidence. Safe drinking water and water quality are fundamental to everyday life. An incident in the Water Sector could have significant impacts on public confidence. Fostering and enhancing the relationships between utilities, government, and the public can mitigate negative perceptions in the face of an incident.	
Objective 1	Communicate with the public about the level of protection and resilience in the sector and provide outreach to ensure the public's ability to be prepared for and respond to a natural disaster or manmade incident.
Objective 2	Enhance communication and coordination among utilities and Federal, State, and local officials and agencies to provide information about threats by utilizing WaterISAC and other information-sharing networks.
Objective 3	Improve relationships among all Water Sector partners through a strong public–private partnership characterized by trusted relationships.

Risks

The *National Infrastructure Protection Plan 2013* guides the national effort to manage risk to national critical infrastructure. It emphasises the complementary goals of security and resilience for critical infrastructure assets, systems, and networks and integrates them into an enterprise approach to risk management. It focuses on risk management and partnership to influence at the international, national, regional, State, local, tribal, and owner and operator levels (National Infrastructure Advisory Council, 2016).

The *National Response Framework* is a part of the National Preparedness System and acts a guide for how the Nation should respond to all types of disasters and emergencies. It uses scalable, flexible, and adaptable concepts to align key roles and responsibilities across the USA (National Infrastructure Advisory Council, 2016).

US EPA: The *Public Health Security and Bioterrorism Preparedness and Response Act* requires drinking water facilities serving more than 3,300 customers to conduct a vulnerability assessment and develop an Emergency Response Plan (ERP). Within this, drinking water providers must identify plans, procedures, and equipment that can be used in event of a terrorist or intentional attack, or be used to prevent or mitigate an attack (Water and Wastewater Sector Strategic Roadmap Work Group, 2024).

Similarly, the *American Water Infrastructure Act* requires that all water systems serving more than 3,300 people need to complete a Risk and Resilience Assessment (RRA) and develop or update their Emergency Response Plan (ERP) to incorporate the findings of said RRA. The RRA includes the risk of malevolent acts and natural hazards to the system, the resilience of the supply system (including technology and IT equipment), the monitoring practices, the financial infrastructure, the use/handling/storage of chemicals, and the operation and maintenance. This provides a regulatory driver to assess the risks to water supply assets from a range of threats and evaluate and implement suitable operational and capital strategies to improve the system (US EPA, 2025; US EPA, 2025).

The US EPA state that a water system must be able to maintain a high enough pressure to provide the flow rate needed to fight the fire, which is typically 14 m head at a hydrant (US EPA, 2014).

Raw water

Nevada: In Nevada, the *Senate Bill No. 47–Committee on Natural Resources* states that the State must '*manage conjunctively the appropriation, use and administration of all water in the State, regardless of the source*'. It also requires the preparation of a water budget, in which an inventory of groundwater for each basin located within or in part in the State is calculated and maintained (Senate Bill No. 47–Committee on Natural Resources, 2017). Senate Bill No. 140–Committee on Natural Resources states that 10% of the total remaining groundwater be reserved for groundwater that has no committed use (Senate Bill No. 140–Committee on Natural Resources, 2019).

Pumping

Iowa: The Iowa Water Wise report states that pumping capacity can be used to infer the level of water conservation required by customers (Iowa Association of Municipal Utilities, 2013):

- 75% pumping capacity – voluntary conservation
- 85% pumping capacity – restricted water use
- 95% pumping capacity – water rationing

Michigan: The *Michigan Drinking Water and Environmental Health Division Supplying Water to the Public Code* state that a pumping facility should have sufficient capacity to meet supply demands when the largest unit is removed, and that each unit of a pumping facility should be able to be removed from service without it interrupting the supply of water. All pumping facilities should be designed to maintain minimum pressure of 3 m gauge in all buried suction piping and suction piping subject to flooding. Finished pumping facilities taking directly from a distribution system should maintain a minimum pressure of 25 m under normal operating conditions and 14 m during emergencies (e.g. firefighting) within the distribution system. The system should also have sufficient capacity to meet peak demand whilst maintaining the aforementioned minimum pressure (Department of Environment, Great Lakes, And Energy, 1976).

Storage

New Jersey: The *New Jersey Water Supply Management Act Rules* state that the minimum storage requirements listed in Table 3.5 apply where auxiliary power and interconnections must be able to supply at least 50 percent of average production independently. It also states that where possible, storage should be spread out and located at different points in the water supply system (Water Supply Management Act Rules, 2007).

Table 3.5 New Jersey Water Supply Management Act Rules minimum storage requirements (Water Supply Management Act Rules, 2007)

Source	Minimum storage (% of average daily demand)
Single, prime source, no interconnection(s), no auxiliary power at water source	100
Single, prime source, no interconnection(s), auxiliary power provided at water source	80
Single, prime source with interconnection(s)	50
Multiple sources, no interconnection(s), no auxiliary power at water source	80
Multiple sources, no interconnection(s), auxiliary power provided at water source	50
Multiple sources, with interconnection(s)	50
Multiple sources, interconnection(s), auxiliary power provided at water source	30
Multiple sources, interconnection(s), auxiliary power provided at water source, distributing more than an average of ~190 million litres per day[a]	20

a: converted from gallons to litres

Distribution

The *Joint Municipal Water and Sewer Commission* state that there should be a minimum residual pressure of 17.5 m or no less than 14 m during instantaneous demand such as fire flow. Where pressures within the distribution system are above 56.3 m, pressure regulators are required (Joint Municipal Water and Sewer Commission, n.d.).

Alaska: The *Alaska Drinking Water Regulations* require plans for new distribution systems and associated facilities to have a minimum pressure of 14 m at the highest elevation or pressure zone of a distribution main be maintained under peak design demand. The plans must also show that it has capacity for meeting minimum consumption needs (Alaska State Legislation, 1999).

Colorado: The *Denver Water Operating Rules* state that "*Denver Water may require that the Water System be replaced, extended or otherwise modified' in order to ensure adequate water supply for customers and the fire protection service*" (Denver Water, 2007).

Hawaii: The *Hawaii Department of Water Supply Amended Rules & Regulations* state that "*the Department shall make every effort to maintain sufficient pressure in its water mains, but accepts no responsibility for maintaining such pressure*" (Department of Water Supply, County of Hawai'i, 2016).

Mississippi: The *Mississippi Rules and Regulations Governing Public Utility Service* state that minimum pressure within a distribution network must not fall below 24.5 m or rise above the maximum pressure of 88 m at customer's service connections. Within rural locations where there is no fire service, the minimum pressure may be 14 m (Mississippi Administration, n.d.).

New Jersey: The *New Jersey Water Supply Management Act Rules* state that the 'balances and interrelationships' of the supply network and related facilities must ensure a minimum pressure of 14 m "*at street level, in all parts of the distribution network, under all required flow conditions*" (Water Supply Management Act Rules, 2007).

Nevada: The *Nevada Administrative Code* state that residual pressure within the distribution system must be a minimum of 14 m during conditions of fire flow and fire demand experienced during maximum day demand, minimum of 21 m during peak hour demand, and a minimum of 28 m during maximum day demand. Normal water velocities of 2.5 m/s during all conditions of flow other than fire flow must be maintained to avoid high head losses, unless approved by the Division/district board of health (Navada Legislation, 2004).

Supply

Many western states have enacted statutes requiring a local government level determination of the adequacy of available water supplies to support new developments. This recognises that the adequacy of water for new developments is a matter of statewide concern due to its importance in the preservation of public health, safety, and welfare and the environment (Green & Castle, 2017).

California: The *California Water Code* states that the governing body of a water supplier "*shall declare a water shortage emergency condition to prevail within the area served by such distributor whenever it finds and determines that the ordinary demands and requirements of water consumers cannot be satisfied without depleting the water supply of the distributor to the extent that there would be insufficient water for human consumption, sanitation, and fire protection*." However, a public hearing must precede this except in the event of a wildfire, de-energisation event (mass disconnection of energy supply), or a breakage or failure of a dam, pump, pipeline, or conduit causing an immediate emergency (California Water Boards, 2024).

The *California Water Code* also states that every urban water supplier must assess the reliability of its water service during normal, dry, and multiple dry water years as part of its urban water management plan. The assessment compares the total water supply sources available to the long-term total projected water use over the next 20 years in 5-year increments for a normal year, a single dry year, and a drought lasting five consecutive years. The water supplier must also include a drought risk assessment when considering developing the demand management measures and water supply projects and programs. The drought risk assessment should include a reliability determination for each water source under a variety of water shortage conditions; a comparison of total water supplies available, and the projected water use during a drought period; and consideration of historical droughts, potential changes to projected supply and demand under climate changes, and potential regulatory changes (California Water Boards, 2024).

The *California Water Code* states that if water supplies are deemed or projected to be insufficient the water supplier should provide the city/county plans for acquiring additional water supplies. The plans should include estimated costs and how these will be financed; all permits, approvals or entitlements that will likely be required; and the anticipated time it will take to acquire the additional water supplies (California Water Boards, 2024).

The Code also states that no-one should go without running water during a drought, highlighting that California can take steps to implement more proactive drought planning to mitigate and prevent significant impacts on drinking water for vulnerable communities (California Water Boards, 2024). Each urban water supplier shall prepare and adopt a water shortage contingency plan which contains water supply reliability analysis, and the procedure used to conduct an annual water supply and demand assessment which contains the decision-making process to determine water supply reliability and the data and methods used to evaluate the water supply reliability during the current year and dry year (California Water Boards, 2024).

Delaware: The *Delaware Water Code* states that 'adequate supply' indicates a volume of water which meets or exceeds the projected demand. This is determined with the assumption that a drought of record conditions exists during the projected year (Legislative Council, General Assembly, 2011).

Mississippi: The Mississippi State Department of Health, Bureau of Public Water Supply's *Minimum Design Criteria for Mississippi Public Water Systems* states that a "*water system should be designed to supply all existing homes and lots in the certificated area, whether or not they have requested service. A reasonable growth factor should be included*."

The Mississippi Code *Title 51. Waters, Water Resources, Water Districts, Drainage, and Flood Control* states that the water distribution system should be designed so that under peak demand conditions the capacities at the point of outlet discharge shall be no less than the values shown in Table 3.6 (Mississippi legislation, 1972).

Table 3.6 Required capacities at the point of outlet discharge as stipulated by the Mississippi Code Title 51 (Mississippi legislation, 1972)

Fixture supply outlet serving	Flow rate (l/m)	Flow pressure (m head)
Bathtub, balanced pressure, thermostatic or combination balanced pressure/thermostatic mixing valve	15	14
Bidet, thermostatic mixing valve	7.5	14
Dishwasher	10	5.6
Laundry tray	15	5.6
Lavatory	3	5.6
Shower, balanced pressure, thermostatic or combination balanced pressure/thermostatic mixing valve	9.5	14
Sillcock, hose bibb	19	5.6
Sink	6.5	5.6
Water closet, flushometer tank	6	14
Water closet, tank, close coupled	11	14
Water closet, tank, one-piece	22.5	14

Note: These values have been converted from gallons per metre and PSI

New Jersey: The *New Jersey Water Supply Management Act* states that during a state of water emergency the commissioner is empowered to (amongst others), order persons to reduce consumption from any water source by a specified amount, use alternative supplies, make emergency interconnections, or cease using said water supply; or order any water supply distributor to reduce or increase supply by a specified. The above must not be in conflict with Federal law or regulations (New Jersey Legislation, 1981).

The *New Jersey Water Supply Management Act Rules* state that to assure the availability of water during times of emergency, the Department may require interconnections to be made. A feasibility study is required to find the most cost-effective option, although this could be waived if it is deemed to cause undue hardship (Water Supply Management Act Rules, 2007).

Nevada: The *Nevada Administrative Code* states that the public water supply system maintains a sufficient capacity to produce and treat water and sufficient storage capacity, enabling it to satisfy the requirements of all users under the conditions of maximum day demand and peak hour demand.

The *Nevada Administrative Code* also states that if the only supply source is water wells, the total capacity of the system must sufficiently meet the greater of maximum day demand, fire flow and fire demand when all the facilities of the system are functioning or average day demand, fire flow and fire demand when the most productive well of the system is not functioning (Navada Legislation, 2004).

The *Nevada Water Regulations* state that a water supplier must notify all users of any works that may affect their supply, as well as the length of time that they will be without water. Notification must happen at least an hour before supply is turned off (unless under exceptional circumstances). Failure to do so renders them liable for all damages associated with the supply shut off (Las Vagas Code of Ordinances, 1912).

Texas: The *Texas Utility Regulations* state that a "*public utility which provides water service shall plan, furnish, operate, and maintain production, treatment, storage, transmission, and distribution facilities of sufficient size and capacity to provide a continuous and adequate supply of water for all reasonable consumer uses*." During drought, periods of abnormally high usage, or equipment failure leading to an extended reduction in ability to supply water, restrictions may be implemented to limit water usage in accordance with the utility's approved drought contingency plan (Texas Water Code, 2024).

Washington: The *Revised Code of Washington* states that if there are found to be water supply problems, the affected area will be designated as a critical supply area within which no new public water systems can be approved, unless the water purveyor is unable to provide a water service (Washington State Legislation, 1977).

3.2.2 Canada

Canadian guidance defines adequate and reliable supply for firefighting purposes in the *Water Supply for Public Fire Protection: A Guide to Recommended Practice in Canada* (Fire Underwriters Survey, 2020):

A water distribution system is considered to be fully adequate if it can deliver the necessary fire flow at any point in the distribution gridiron for the applicable time period specified […] with the consumption at the maximum daily rate (average rate on maximum day of past 3 years). When this delivery is also possible under certain emergency, or unusual conditions as herein specified, the water distribution system is considered to be reliable. In cities of population in excess of 250,000 (or smaller places with high fire incidents and/or severe hazard conditions) it is usually necessary to consider the possibility of two simultaneous major fires in the area served by the water distribution system.

The guidance says that the water supply system should 'normally' "*be able to maintain the maximum daily consumption rate plus the maximum required fire flow*" but clarifies that in the case of filters in water treatment, this can include overload capacity which may exceed 25%.

The guidance also suggests that less emphasis should be placed on interruptions to supply fed from wells compared to those which affect large numbers of customers, and that there should be allowances made for delays or interruptions to supplies obtained from "*systems or sources not under the control of the municipality or utility*".

In Quebec, sufficient quantities of drinking water is defined as "*adequate pressure and a sufficient volume of water to provide the hourly peak flow, or the flow for the maximum consumption day, and the fire flow*" (MELCCFP, 2023). This level of specificity is not provided in other states. For example, in Alberta the requirement is for "*an adequate quantity of safe drinking water in a reliable manner at all time*" and that this should consider current and foreseeable future needs of the system's consumers (Alberta Government, 2012).

In Quebec and Alberta, pressure at a customer's property must be maintained at a minimum of 15 m during peak demand design flow (Alberta Government, 2012). Furthermore, in Alberta, the water distribution system must be designed to handle a normal operating pressure between 35 m and 55 m under a condition of maximum hourly design flow (Alberta Government, 2012).

Raw water

In Alberta, raw water reservoirs should have a minimum of 2 cells which should be sized to retain about 75% of the annual raw water need. This should be increased in areas of drought to overcome long-term stress. Each cell should be able to be isolated to enable the draining of each cell, as well as their operation in either series or parallel (Alberta Government, 2012).

Pumping

Sufficient pumping capacity is defined as the ability, "*in conjunction with storage when the two most important pumps are out of service, to maintain the maximum daily consumption rate plus the maximum required fire flow at the required pressure for the required duration*". Adequate supplies from these pumps is defined as provision of the required fire flows for the specified duration **at any time during a period of five days with consumption at the maximum daily rate.** This can be fulfilled by spare pumps or prime movers in addition to those elsewhere which can be used via the operation of valves. The requirement to fulfil while the two largest pumps are out of service is dropped for water systems serving less than 25,000 people (Alberta Government, 2012).

The pumps also need to be arranged such that a power line failure or out of action transformer, switch, control unit to other device does not prevent the required fire flows, even during a period of 2 days with consumption at the maximum daily rate. To maximise resilience, power lines should be below ground and have no other consumers between the water treatment plants or pumping stations and the electricity provider (Alberta Government, 2012).

For equipment powered by fuel, at least 5 days' supply should be held, while gas should be supplied from two independent sources, or by dual lines from the same source with 24 h storage, or an alternative fuel/power supply (Alberta Government, 2012).

The Alberta *Guidelines for Municipal Waterworks* recommends using at least three pumps, where two are used and one is on standby. The capacity of the pumps should be that they able to continue to pump water when the largest unit is out of order. Adequate space should also be provided so that additional pumps can be added in the future, as well as enabling safe space for servicing all equipment (Alberta Government, 2012).

Similarly, the distribution system should be designed with at least two pumps in a way that when one pump is out of service, the remaining pumps are able to deliver the maximum hourly design flow of at least ~15.3 m head (Alberta Government, 2012).

Storage

Alberta's *Guidelines for Municipal Waterworks* state that water storage requirements should include emergency storage (in this case a minimum of 15% of projected average daily design flow), fire storage, equalisation storage (approximately 25% of projected maximum daily design flow), and sufficient storage to allow sufficient disinfection contact time (Alberta Government, 2012).

Distribution

Sufficient resilience of water mains is defined as not drastically reducing the flow available to any district as a result of cut-off of any main. A sufficient number of valves is defined as a number such that "*a break or other failure will not affect more than 400 metres of arterial mains, 150 metres of mains in commercial districts, or 250 metres of mains in residential districts*" and that the repair of a valve should normally be completed within 2 days (Alberta Government, 2012).

Water treatment

In Alberta, water treatment plants should be designed to treat the flows projected in the next 10 years with the provision for expansion to handle 20 to 25-year design flows. This design should be based on 110% of the projected maximum daily design flow to account for in-plant losses. Water storage design should also be phased to avoid oversizing. Intake and outfalls, however, should be designed "*for the entire design horizon which is at least 20 to 25 years*" (Alberta Government, 2012).

3.3 Europe

The European Commission 'invited' Member States to ensure a minimum water supply for all citizens, in line with WHO recommendations. They further recommended that Member States address this issue at a national level in a manner the state deemed appropriate, with the caveat that actions should constitute improving access to water for all (European Parliament, 2020).

It also committed to continue to "*improve access to safe drinking water […] for the whole population through environmental policies*".

In addition, the EU has recently published its European Water Resilience Strategy (European Parliament, 2025). It notes impacts of water scarcity on economic development, but, rather than focussing on supply, suggests that *"water efficiency is key and must come first"* and that *"increased supply should be the last resort option"*. It recommends these water efficiency efforts are focussed on *"the most intensive water users, both current and future",* noting the requirements of the Industrial Emissions Directive which *"ensure that large industrial actors progressively reduce water demand, enhance water efficiency and improve water reuse across production processes"*. Overall, it sets a cross-EU target of improving water efficiency by at least 10% by 2030, with benchmarks introduced in 2027. When focussing specifically on public water supply, it says the focus should be on reducing leakage, while more effort should also be put on demand management through public awareness and involvement in water management and water pricing.

3.3.1 Belgium

In Belgium, water services provision is mainly under the jurisdiction of the regions and municipalities. In Flanders water companies are permitted through the *Decree of the Flemish Government* of 20 Match 2020 to cut off supply "*in the event of repair, renovation, modification, relocation, maintenance or operation of the public water distribution network*". However, "*every customer is entitled to a basic uninterrupted supply of […] water for household purposes in order to be able to live decently according to prevailing living standards*" which is defined as 15 m^3 of free water per person per year (41 l/p/d) (Ministere de la Communaute Flamande, 1996).

In the Walloon region, customers have a right to "*access to drinking water of sufficient quality and quantity to cover their food, domestic and health needs*" (Le Parlement de Wallonie, 1999). To facilitate this, adaptive pricing is used and the first 30 m^3/p/yr (82 l/p/d) is charged at the lowest rate. This is similar in the Brussels region, but the lowest price block there applies only for the first 15 m^3/p/yr (41 l/p/d). In the Walloon region, the water company is required to provide continuous supply except in situations that "*cannot reasonably be controlled*". The company is to guarantee static pressure at the meter of 20.4 to 102 m head at a minimum flow rate of 300 l/h, but only under "*the network's usual operating conditions, unless the distributor makes provision…relating to the social water fund*". Alternative supply is only required after an interruption exceeds 8 consecutive hours between 6am and 10pm (SWDE, 2007).

3.3.2 Denmark

In an article on benchmarking and security of supply in the utilities sector, the Danish Competition and Consumer Authority they consider the opportunity to include security of supply in the economic efficiency benchmarking of water companies. They choose the metric of "*absence of recommendations to boil*" as their measure of security. In the utilities sector, security of supply has traditionally been measured as the average number of minutes that consumers are without their utility service (Danish Competition and Markets Authority, 2019).

3.3.3 Germany

In Germany water stress is defined as water withdrawals exceeding 20% of the long-term renewable water resources (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, 2023).

German design standards exist for water boosters in multi-storey buildings (DIN 1988-500:2021-05) in order to provide the required delivery pressure (10 m + 4 m per storey), while DVGW technical standard W 400-1 defines the minimum supply pressure for water supply systems as 0.15 m head for systems with firefighting and 5 m otherwise. For firefighting there needs to be sufficient water for 24 m^3/h for 2 hours. Their *Code of Practice* requires pipeline systems to maintain "*continuous supply reliability*" through "*installation of shut-off valves [...] to isolate pipeline sections during emergencies.*"

3.3.4 Ireland

Uisce Éireann (UE) relatively recently added water supply interruptions to their reported indicators. The targeted by the end of 2021 a reduction in the number of interruptions and a higher proportion of interruptions being planned. Its 2040 target is 0.13 hours lost per property per year. It also has a metric for low pressure, reporting the percentage of properties at or above the reference level of 15 m head at the property meter. It is targeting 99.9% by 2040 and targeted a 2% reduction per annum in the number of properties with low pressure in 2020 and 2021. (Irish Water, 2015). UE also acknowledges that "*[w]ater supply within our cities and large towns does not meet international norms for available headroom*". For example, headroom in the Greater Dublin Area has increased from 1-2% in 2016 to 3% in 2025 (Department of Housing, Local Government and Heritage, 2020). WRc has interpreted this headroom as referring to water resources headroom (rather than spare capacity within the water supply system as a whole). However, the wording is ambiguous. UE additionally notes that "*[o]ver the past decade, water supply availability has regularly exceeded demand requirements in the Dublin Water Supply Zone by just 1%-2% (20% excess over seasonal peak would constitute* *normal best practice for a large urban area).*" The appendix on headroom in its WRMP states that, following the UKWIR methodology, the target for the Greater Dublin Area is 8%, and more generally for zones >10 Ml/d is 10%, 1-10 Ml/d is 15%, and <1 Ml/d is 20% (Uisce Éireann, 2021). Typical values in the UK are 3-8%.

In its Strategic Plan, UE also note that it is going to measure the percentage of treatment plants meeting the target capacity headroom. This could be interpreted to mean either the water resources headroom upstream of the works, or the headroom between design and actual throughput. It expected 60% of water treatment plants to meet its headroom target by the end of 2021, 75% by 2027 and 100% by 2040 (Uisce Éireann, 2015). Direct measurements of progress towards these targets could not be found, but Table 3.7 shows the relative proportion of Irish Water's network which is considered to have growth capacity.

Table 3.7 Indication of available capacity to support 2033 population target (Uisce Éireann, 2025)

Category	Number of Settlements	Number of WRZs
Capacity Available[10]	266 (30.7%)	134 (41.9%)
Capacity Available - LoS improvement required[11]	178 (20.5%)	29 (9.1%)
Capital Investment Required[12]	17 (2.0%)	7 (2.2%)
Potential Capacity Available - LoS improvement required[13]	406 (46.8%)	150 (46.9%)

10 Capacity Available = Capacity Available to meet 2033 population targets.

11 Leakage reduction and/or capital investment will be required to maintain/improve levels of service as demand increases. These proposals will be developed & prioritised through the National Water Resources Plan and investment planning process

12 Capacity constraints exist and additional analysis of Pre-connection Enquiries and Connection Applications will be undertaken as required by UÉ on an individual basis considering their specific load requirements. Improvement proposals will include but are not limited to leakage reduction and/or capital investment. These proposals will be required to maintain/improve levels of service as demand increases. These proposals will be developed and prioritised through the National Water Resources Plan and investment planning process.

13 Capacity Not Available - capital investment required to increase capacity. These proposals will be developed and prioritised through the National Water Resources Plan and investment planning process.

3.3.5 Italy

In Italy, households are encouraged to install storage tanks guaranteeing the water supply and an adequate water distribution pressure during the interruptions on the network caused by the water crisis now generalised and repeated over time (Regional Law 22 August 2022, No. 26, Measures to support the population aimed at limiting the impact of water shortage, 2022).

In Italy Regional and Basin Authorities are responsible for environmental regulation and infrastructure planning (Act No. 36 on Water Resources, 1994 (Galli)). Regional Laws, such as in Lazio, use this to define both *availability* and access to drinking water are "*guaranteed as inalienable and inviolable rights of the person*" in accordance with a public bill signed by over 400,000 Italians raised to the Italian Parliament in 2005 (Forum Italiano per i Movimenti dell'Acqua during the II National Meeting in Florence, 2005) (Institute Environmental Law Research Centre, 2008). Water use for "*food, hygiene and human care*" has priority over all other water uses and "*must always be guaranteed*". However, what this means in practice is not clear (Lazio Legislation, 2014).

Similarly, Italian Regional Act No. 5 on the protection and public management of water resources states that '*the use of water for food, hygiene and human care is a priority over other uses of the same surface or groundwater body… [and that] the use of water for agriculture and animal feed shall take priority over other uses, with the exception of [those previously mentioned]*' (Lazio Legislation, 2014). This could be considered similar to the WIA requirements of water for domestic purposes.

3.3.6 The Netherlands

Dutch drinking water companies must have capacity to be self-sufficient so that during the event of a failure, the drinking water supply system must be able to continue to function for at least ten days (based on average daily consumption) (OiEau, 2023). This is interpreted as water companies having their own emergency power generators and fuel stocks, as well as large stocks of chemicals (VEWIN, 2025).

Water companies have priority over raw water ahead of energy (but behind flood defence, preventing settlement and preventing irreversible environmental damage) (Netherlands State Gazette no. 548, 2009).

3.3.7 Norway

The Norwegian *National Sustainability Strategy for the Water Industry* stated that there is a subsidiary goal which includes measures to improve security of supply and that unplanned interruptions to water supplies should not occur on average once every 10 years per customer (Norwegian Water, 2017).

3.3.8 Portugal

In October 2024, Portugal implemented new compensation rules which require water utilities to compensate customers for service failures, including (TPN/Lusa, 2024):

- Water supply interruptions
- Insufficient water pressure
- Other service quality issues.

Portugal's water pressure standards for supply systems are technically defined through operational guidelines rather than explicit legislative thresholds.

3.3.9 Sweden

No relevant insights were found when reviewing water regulation in Sweden.

3.3.10 Switzerland

The Swiss *Water Act* requires municipalities to supply water to building zones, supply water to other zones when possible, and not have any properties fed by a single source of supply unless it's unaffordable to do so. Furthermore, if there is either insufficient groundwater quantity or quality, water should be replenished to rectify this and an up-to-date groundwater quality plan must be in place (Die Präsidentin Esther Guyer & Der Generalsekretär Moritz von Wyss, 2023).

There is also a minimum residual flow requirement for watercourses used as drinking water sources (Table 3.8).

Table 3.8 Minimum residual flow from permanently flowing watercourses used for water withdrawal (Federal Act On the Protection of Waters, 1991)

Permanently flowing watercourse flow rate	Minimum residual flow
Up to a flow rate Q_{347} of 60 l/s	50 l/s
and for each further 10 l/s of flow rate Q_{347}	*8 l/s*
For a flow rate Q_{347} of 160 l/s	130 l/s
and for each further 10 l/s of flow rate Q_{347}	*4.4 l/s*
For 500 l/s of flow rate Q_{347}	280 l/s
and for each further 100 l/s of flow rate Q_{347}	*31 l/s*
For 2,500 l/s of flow rate Q_{347}	900 l/s

Permanently flowing watercourse flow rate	Minimum residual flow
and for each further 100 l/s of flow rate Q_{347}	*21.3 l/s*
For 10,000 l/s of flow rate Q_{347}	2,500 l/s
and for each further 1,000 l/s of flow rate Q_{347}	*150 l/s*
From 60,000 l/s of flow rate Q_{347}	10,000 l/s

flow rate Q_{347}: means the flow rate which, averaged over ten years, is reached or exceeded on an average of 347 days per year and which is not substantially affected by damming, withdrawal or supply of water

3.4 Asia and Africa

3.4.1 China

No specific requirements on water undertakers relating to sufficiency or resilience of water supply were identified. However, the *Water Law of the People's Republic of China* specifies that domestic water demand of existing inhabitants are given primacy over the use of water resources ahead of agriculture and industry, navigation, and then urban growth and development of new water intensive industry. An integrated approach is mandated for water resource planning, considering existing water resources alongside new sources of supply, reuse and demand management (Water Law of the People's Republic of China, 2002).

3.4.2 Hong Kong

Due to its highly variable rainfall and lack of natural water resources, Hong Kong has had to create a resilient water system through diversification of sources (including bulk import from China and non-potable water supplies) and interconnectivity in the network (Sai-wai, 2017; WSD Hong Kong Government, n.d.; WSD Hong Kong Government, n.d.; WSD Hong Kong Government, 2015). However, no relevant insights were found when reviewing water regulation in Hong Kong.

3.4.3 Japan

The Japanese *Water Supply Service Act* (also known as the *Waterworks Act*) stipulates that the water supply system must be able to provide the "*necessary volume*" of water "*at a fixed level of pressure or higher*"[14]. This includes the stipulation that reservoir capacity is great enough to "*supply the required amount of raw water even during times of drought*". Water supply facilities should be sufficiently durable to withstand relevant load including water pressure, earth pressure, and seismic force (Water Supply Act (Tentative translation), 1957).

[14] Quotations have been translated

The World Bank state that the ministerial ordinance *MHLW's 2000 Ministerial Ordinance for Technical Standards of Water Supply Facilities* was brought in to provide improved performance criteria, promote increased supply safety and resilience, and provide criteria for performance against natural hazards (World Bank Disaster Risk Management Hub, 2017). Amendments made in 2008 included recommendations for resilience, such as integrating disaster risk management into WSS regulations and asset management systems, establishing emergency preparedness plans and support agreements, and building early warning systems and emergency water storage. Additionally, utilities should develop robust communication systems, institutionalise business continuity planning (BCP), and train personnel regularly to ensure rapid restoration of essential services during disasters. The Japan Water Works Association and the Japan Sewage Works Association have also developed guidelines for, and established a mutual support network of utilities in case of, disasters (World Bank Disaster Risk Management Hub, 2017).

The Ministry of Health and Labour Welfare state that waterworks facilities must consistently supply safe, purified water at required pressure and quality, efficiently respond to demand changes, and ensure reliability through redundance, dispersed infrastructure, and backup systems (Ministry of Health and Labour Welfare, 2004). They must be designed to minimise service disruption during emergencies, support rapid recovery, conserve the environment, and remain structurally safe under various natural conditions.

3.4.4 Singapore

In Singapore property owners, developers, or consumers to install adequate water storage and necessary equipment to maintain a continuous and steady water supply within their premises. Additionally, consumers seeking uninterrupted water supply must ensure their own installations meet these standards (Public Utilities Board, 2002).

3.4.5 South Korea

The *Basic Law for Disaster and Safety Management* in South Korea mandates water suppliers to implement measures for stable water supply and requires the Minister of Environment to develop a comprehensive water supply and demand plan every 10 years. It also obligates suppliers to prepare emergency supply plans, respond to accidents or disasters, and promptly inform users of any supply restrictions (Basic Law for Disaster and Safety Management, 2012).

In addition, when prolonged droughts or similar conditions make normal water distribution challenging, the state should prioritise allocating water resources for essential human needs and critical economic activities, such as drinking water (Water Resources Survey, Planning and Management Act, 2018).

3.4.6 South Africa

Cape Town's *Water Strategy* was published following its 3-year drought (2015-2018), which was a 1-in-590-year event. The drought was notable for 'Day Zero', which was projected to be the day that total dam levels reached 13.5% storage capacity. This was never reached, but at this point capacity would have provided 25 l/p/d for 3 months (projected) before dam capacity fell to 10%, below which it would have been difficult to continue to abstract more water (City of Cape Town, 2019).

The Strategy states that (City of Cape Town, 2019):

- Their proposed build programme will reduce the likelihood of future severe water restrictions as it is based on a higher reliability standard (99.5%) than previously used (98%).

- Whilst the proposed new infrastructure will not be required or used all the time, the investment would not have been wasted as it provides insurance against drought "*the future is uncertain, and the cost of very severe restrictions is much higher than the cost of insuring against this likelihood*".

- A greater proportion of Cape Town's water supplies will be met from alternative sources such as groundwater, desalination, and reuse. In the medium- and longer-term desalination will likely contribute an increasing share to the supply mix, as it is scalable and not reliant on rainfall.

4. Frameworks and guidance to support water supply sufficiency and resilience

4.1 Global perspectives

The OECD *Principles of Water Governance* form a high-level framework for guiding governments and stakeholders in designing and implementing effective water policy (OECD, 2015). This includes best practice relating to building resilience against water-related risks such as water scarcity. Best practice includes being proactive, rather than reactive, integrating climate adaptation and disaster risk reduction into water management strategies, and supporting sustainable development by ensuring water security for the future needs of the environment, economy and population.

EurEau (2024) highlights the need for strong coordination between all levels of authorities in water resource planning and management. Governance at the river basin level should be strengthened, using existing River Basin Management Plans (RBMPs) to support integrated, cross-sectoral planning. Adaptive water resource plans should be developed with active stakeholder collaboration and aligned with existing tools.

Hopkins (2023) identified the abstract concept of "reliable supply" for public water suppliers is a weakness within legislation. It was identified that there was no consistent method to define, evaluate, and report reliable water supply. The term "reliable water supply" lacks a clear definition in the Western United States, an area where water resources are scarce and such a definition would be particularly valuable (Hopkins & Sowby, 2024).

When considering available water in storage the impacts of water quality need to be considered. It is often the case that reservoirs cannot be drawn down below, e.g., 20% before suspended solids and turbidity levels become higher than the maximum treatable rate of the treatment plant (Amarasinghe, 2014).

There are also reports which discuss water-related risks and guidelines for risk management such as (The Global Compact, 2014):

- 'Understanding Water Risks and Investigating Shared Risk in Water' by WWF
- 'Watching Water: A Guide to Evaluating Corporate Risks in a Thirsty World' by JP Morgan and WRI
- 'Water Scarcity & Climate Change: Growing Risks for Businesses & Investors' by Ceres and Pacific Institute

- ‘At the Crest of a Wave: A Proactive Approach to Corporate Water Strategy’ by Pacific Institute and BSR
- Arup’s City Water Resilience Approach is a methodology for building capacity into water systems in order to achieve resilience against shocks (Arup, 2022)

4.2 International standards

Assurance regarding corporate resilience could also be provided through certification against or compliance with the principles of common standards such as:

- ISO 22301 Business Continuity Standard
- ISO 55001 Asset Management
- ISO 31000 Risk Management
- AWWA J100-21 Risk and Resilience Management of Water and Wastewater Systems[15]
- BS EN 15975 Security of drinking water supply. Guidelines for risk and crisis management
- ISO 22316:2017 Security and resilience – Organizational resilience – Principles and attributes
- ISO 24596:2024 Drinking Water, Wastewater and Stormwater Systems: Guidelines for Hardening Infrastructure
- WIS 4-01-04 Issue 1 Specification for the audit of water industry risk assessments and risk management processes
- Certification of IT/SCADA systems as cyber secure, e.g. national cyber security centre action plan.

Assurance could take the form of certification or internal or external audits. This assurance and governance framework typically would include:

[15] There is also an AEM Corp PARRE for J100 tool that helps water systems stay compliant with America’s Water Infrastructure Act (AWIA) of 2018, Section 2013

- Technical auditor
- Financial auditor
- BS 65000 (Organisational Resilience) Audits
- Internal audits, in line with ISO9001 (Quality Management Systems) and ISO14001 (Environmental Management Systems).

A recent UKWIR study (UKWIR, 2017) suggested that a water industry-specific standard based e.g. on ISO 22301 (standard for business continuity management) could be created to assess whether reasonable steps have been taken to achieve resilient and reliable water network and whether they follow the standard (audit against objectives). It suggests that the outcome would be binary (compliant or non-compliant).

4.3 Frameworks

This section outlines frameworks that could be used by water companies to demonstrate adhering to best practice and performing due diligence with respect to maintaining a resilient and sufficient water supply. The frameworks have been summarised in Table 4.1. More detail is provided in Appendix D.

Table 4.1 Frameworks for ensuring resilience

Framework	Scope	Author	Link	Assessment
How tough is WASH	• Infrastructure • Environment • Management • Level of institutional support • Supply chain • Community governance and engagement	University of Bristol	How Tough is WASH Climate Resilience Framework A field guide to assess climate resilience of water supplies	Other frameworks are more specific and relevant to the English and Welsh water industry.
Vulnerability Self-Assessment Tool	• Infrastructure	US EPA	https://vsat.epa.gov/vsat/	This tool could be used as a template for the UK to guide water companies through assessment of risks, critical assets and countermeasures. However, in its current form it is applicable only to the US context.
Effective Utility Management	• Financial • Customer experience and satisfaction • Operations • Performance • Staff • Sustainability	US EPA	Effectively Managed Utilities Primer	This is a good high-level framework for assessing basic overall business resilience is too detached from the end experience received by customers and is not sufficiently detailed or prescriptive to be a useful assurance tool or regulatory framework.
Climate Resilience Evaluation and Awareness Tool	• Environment • Shocks, stresses and hazards	US EPA	https://www.epa.gov/crwu/climate-resilience-evaluation-and-awareness-tool	This framework shows potential for UK deployment. However, this would require data gathering (particularly on the costs

Framework	Scope	Author	Link	Assessment
				and benefits and quantification of risk impacts).
Safe & SuRe	• Mitigation, adaptation, coping and learning with respect to emerging threats	University of Exeter	[SAFE & SURE]()	This provides useful and clear definitions of what makes a system resilient.
Framework for resilience performance measures	• Measurement	UKWIR	(UKWIR, 2017)	We agree that this represents good practice for the definition of resilience indicators.
Resilience framework	• Community governance and engagement • Mitigation, adaptation, recovery with respect to current and emerging threats	UK government	(HM Government, 2022)	The recommendations under this framework to communicate and collaborate cross-sector and with local groups should not be forgotten, but this is detached from end-user experience so may be inappropriate as the basis for DWI metrics and standards.
Keeping the Country Running	• Community governance and engagement	UK Cabinet Office	(Cabinet Office, 2011)	The existing guidance to create and update resilience plans and monitor investment spend could be used as the basis for assurance of resilience. The ‘4Rs’ framework has the advantage of being well known and commonly adopted in the UK

Framework	Scope	Author	Link	Assessment
				but should be compared with others such as the Safe & SuRe framework.
Water safety planning	• Mitigation and, adaptation with respect to current threats	British Standards Institute	BS 8680:2020 Water quality. Water Safety Plans Code of practice.	As an existing planning activity that requires water companies to assess and quantify risks to their system and consider mitigation, water safety planning may offer low effort / efficient means of providing quantification, benchmarking and regulatory assurance of water supply resilience and sufficiency. Benefits include the segmentation of the water system (which we have chosen to adopt in this report), but limitations include the lack of consistent approach to water safety planning and reporting, infrequency of updates, consideration of current as opposed to future risks, and a potential bias towards risks to water quality as opposed to quantity.
Utility Resilience Index	• Operations • Staff • Emergency response • Infrastructure • Business continuity	Water Research Foundation	(Water Research Foundation, 2023)	The framework is intended to provide a common structure but allow companies to tailor the resilience definition and resilience outcomes to their specific context. It is focussed on driving improvement, so could be used to demonstrate progress. However, while freedom with determining

Framework	Scope	Author	Link	Assessment
				how to ensure resilience is likely to be beneficial, it is likely that a common set of resilience outcomes and a common definition of resilience would be most beneficial for the DWI's context. As such, this is likely to be more suitable as an internal tool rather than a regulatory framework.
Yorkshire Water resilience framework	• Corporate • Financial • Operational	Yorkshire Water	(Yorkshire Water, 2018)	This framework appears transferable. However, an agreed list of shocks and stresses would be required.
Wessex Water resilience framework	• Mitigation and, adaptation with respect to current and emerging threats	Wessex Water	(Wessex Water, 2023)	This framework appears robust, but an element of prioritisation or quantification may be required to make it feasible in practice for all risks facing the business.
Resilience wheel	• People • Infrastructure • Environment • Infrastructure • Financial • Governance	Arup	(Dŵr Cymru Welsh Water, 2018)	The wheel lacks practical use for DWI's purposes

Framework	Scope	Author	Link	Assessment
United Utilities resilience metric	• Infrastructure • Measurement	United Utilities	(United Utilities, 2017)	Assessing risk (consequence and probability) and adjusting for control factors reflects best practice.
Water resilience assessment framework	• Socio-economic • Governance • Infrastructure • Measurement	CEO Water Mandate	Water resilience assessment framework Resilience Scoring Tool	The Water Resilience Assessment Framework appears to be well regarded and widely adopted. It offers a suitable framework and common language and allows for scoring of resilience for benchmarking and comparison, but its generality could make it challenging to apply.

5. Overview of sufficiency and resilience in water supply

5.1 Introduction

The following chapter discusses approaches for ensuring sufficiency and resilience from source to tap.

5.2 Metrics

Water companies typically measure and internally report a number of metrics and indicators to understand asset health, performance and serviceability. While these would be too narrow and low-level for regulatory reporting and assurance / checking compliance with duties, a possible approach would be to ensure that companies are suitably and sufficiently monitoring and understanding their assets and responding to trends and emerging risks. For each stage of the DWSP we have therefore highlighted examples of operational metrics which the DWI might wish to recommend. That is, the DWI would assess the appropriate use of operational metrics such as those discussed.

Metrics which are suitable for more than one aspect of water supply are indicated by the use of a * after the name. A full explanation of these metrics is included in one section with cross-references to this explanation included elsewhere to avoid duplication.

5.3 Summary

Table 5.1 summarises the KPIs and metrics used to measure resilience and risk, whether they are leading or lagging, and what stage of the DWMP they relate to. Leading indicators predict future outcomes, whereas lagging indicates reflect past performance.

Table 5.1 Relevance of metrics in subsequent chapters aligned to DWSP stages

Indicator or metric	Type	Report ref.	Lead or lag?	Stage				
				Raw water	Water treatment	Strategic distribution and potable water storage	Local distribution	Consumer
SoSI and SDBI	KPI	6.2.1	Lag	✓				
Water situation reporting	KPI	6.3.1	Lag	✓				
Water resources risk assessment	KPI	6.3.1	Lead	✓				
Reservoir system performance	KPI	6.2.2	Lead			✓		
Catchment risk scores from Drinking Water Safety Plans	KPI	6.3.2	Lead	✓	✓			
Water security indices	KPI	6.2.3	Lag	✓			✓	
Expected availability	KPI	7.2.1	Lead					✓
SEMD compliance	KPI	7.2.3	Lag		✓	✓	✓	✓
Population serviced by critical works	KPI	7.2.4	Lag				✓	
Unplanned maintenance	KPI	7.2.5	Lag	✓	✓		✓	
Historic non-availability	Operational metric	7.3.1	Lag	✓	✓	✓	✓	

Indicator or metric	Type	Report ref.	Lead or lag?	Stage				
				Raw water	Water treatment	Strategic distribution and potable water storage	Local distribution	Consumer
Trend in Compliance Risk Index	Operational metric	7.3.2	Lag		✓	✓	✓	
Hours reactive maintenance relative to total maintenance hours	Operational metric	7.3.3	Lag		✓	✓	✓	
Number of critical alarms / number of alarm points per time period	Operational metric	7.3.4	Lag		✓	✓	✓	
Number of sub-threshold alarms / number of alarm points per time period	Operational metric	7.3.5	Lag		✓	✓	✓	
Cumulative sum final water turbidity or similar SPC trend	Operational metric	7.3.6	Lag		✓			
Post-clarification turbidity (absolute value of headroom to target)	Operational metric	7.3.7	Lag		✓			
Trend in nominal clean bed headloss	Operational metric	7.3.8	Lag		✓			

Indicator or metric	Type	Report ref.	Lead or lag?	Stage				
				Raw water	Water treatment	Strategic distribution and potable water storage	Local distribution	Consumer
Number of unplanned process shutdowns	Operational metric	7.3.9	Lag			✓	✓	
Design storage	KPI	8.2.1	Lag			✓		
Population served by critical potable water storage/trunk mains	KPI	8.2.2	Lag			✓	✓	✓
Population served by isolated supply systems	KPI	8.2.3	Lag			✓	✓	✓
Capital schemes delivered	KPI	8.2.4	Lead	✓	✓	✓	✓	
Unplanned Maintenance	KPI	8.2.5	Lag	✓	✓	✓		
Proportion of customers fed from storage	KPI	8.2.7	Lag		✓			✓
Supply interruptions	KPI	9.2.1	Lag					✓
Number of properties at risk of loss of supply from failure of a single source of supply	KPI	9.2.2	Lag				✓	✓
Emergency preparedness	KPI	9.2.3	Lead		✓	✓	✓	✓

Indicator or metric	Type	Report ref.	Lead or lag?	Stage				
				Raw water	Water treatment	Strategic distribution and potable water storage	Local distribution	Consumer
Population at Risk from Large Scale Interruptions	KPI	9.2.4	Lead					✓
Minimum supply pressure & minimum level of service	KPI	9.2.6	Lag			✓	✓	✓
Global Resilience Analysis-Based Benchmark Framework	KPI	1.1.1	Lead			✓	✓	
Pumping station outages	KPI	9.2.8	Lag			✓	✓	
Redundancy	KPI	9.2.9	Lead	✓	✓	✓	✓	
Service reduction rate	KPI	9.2.10	Lag				✓	
Hydraulic modelling metrics	Operational metric	9.3.6	Lag/ Lead			✓	✓	
Usage restrictions	KPI	10.2.1	Lag	✓				✓
Customer satisfaction	KPI	10.2.2	Lag					✓
Number of customers to benefit from a second source of supply / alternative source of	Operational metric	9.2.2	Lead			✓	✓	✓

Indicator or metric	Type	Report ref.	Lead or lag?	Stage				
				Raw water	Water treatment	Strategic distribution and potable water storage	Local distribution	Consumer
supply sufficient to last 24 hours								
Number of interventions which remove a single point of failure	Operational metric	9.2.2	Lag			✓	✓	
Whether sites have an emergency plan which includes the operation of redundant energy and water systems and contains the established essential elements	Operational metric	10.2.3	Lead					✓
Whether power demands can be met by off-grid sources	Operational metric	10.2.3	Lead					✓
Whether the site has multiple electricity and water feeds	Operational metric	10.2.3	Lead					✓
Frequency of previous outages	Operational metric	10.2.3	Lag					✓

6. Sufficiency and resilience in raw water systems

6.1 Approaches

The key approach for ensuring sufficiency and resilience of raw water is water resource planning and drought planning (Loucks & van Beek, 2017). This approach is taken by many countries across the world, and although the details and specifications can differ, the general approach remains the same. In water resource planning, resilience is discussed alongside related terms such as robustness and sustainability, each offering a different lens through which system performance and longevity are evaluated (Hwang, 2018). Resilience-informed approaches to water governance remain fragmented. The dominant focus continues to lie in conventional frameworks, particularly engineering resilience (Rodina, 2018). There has been a recent shift in the discourse towards water security, which underscores the need to incorporate both economic and ecological concerns (Mishra, et al., 2021).

In many countries, economic priorities frequently take precedence over environmental imperatives leading to the degradation of ecosystems. This environmental decline often disproportionately affects marginalised communities and results in the destruction of vital livelihoods (Pahl-Wostl & Knüppe, 2016). This includes impacting the resilience of raw water availability for water supply.

Ensuring water security in the face of environmental change necessitates an approach that embraces the diversity of freshwater ecosystems (Mishra, et al., 2021). Importantly, a truly water-secure future requires a careful balance of social, environmental, and economic considerations, integrating both hard infrastructure and soft governance measures to manage and safeguard water resources effectively. However, Louks and van Beek (2017) note that most approaches can provoke conflict due to the complex trade-offs that need to be considered in water resources planning.

6.1.1 Water resources management planning

In the UK, the 1976 drought highlighted the importance for water resource sufficiency and resilience. Water Resource Management Plans (WRMPs) are produced by water undertakers in England and Wales to suitably plan a secure water supply in the context of water resource availability (Ofwat, EA & NRW, 2023). Scotland and Northern Ireland have similar plans that have some key differences as shown in Table 6.1. The Northern Ireland plan includes both water resource security and supply resilience through identifying potential resilience issues and considering options for increasing resilience (NI Water, 2020).

Table 6.1 Water resource planning periods in the UK

Country	Plan Title	Minimum Time Horizon	Typical Refresh Timeframe
England	Water Resource Management Plan	25 years	5 years
Wales	Water Resource Management Plan	25 years	5 years
Scotland	Water Resource Plan	25 years	6 years
Northern Ireland	Water Resource and Supply Resilience Plan	25 years	6 years

Scotland uses the Water Supply Evaluation Framework (WSEF), developed by the Water Research Foundation, to inform its water resources plan. The framework provides a structured method of assessing resource capacity and identifying risk areas. The modules of the WSEF are (Water Research Foundation, 2018):

- *Module 1 - Scoping and Goals* provides guidance on Integrated Water Resources Management (IWRM) resulting in definition of options, constraints, and planning horizon.

- *Module 2 - Risks and Uncertainties* details strategies for assessing and prioritising risks and uncertainties.

- *Module 3 - Level of Service and Performance Metrics* provides give utilities guidance on setting targets for levels of service and performance metrics resulting in a set of metric to measure the performance of the system under shocks and a level of service defining acceptable performance.

- *Module 4 – Evaluation Approach* focusses on measurement of the performance of the water resources system and developing an Integrated Water Management Plan (IWMP).

- *Module 5 – Modelling and Tools* creates a list of modelling features and improvements that can be made to existing models to implement the features.

Similar information is identified through the WRMP and Water Resource & Supply Resilience Plan processes, although neither specifically references the WSEF. The general steps for the different UK approaches are summarised in Table 6.2.

Table 6.2 Water resources planning stages in the UK (Environment Agency, 2023)

Stage	England & Wales	Scotland	Northern Ireland
1	Baseline Supply-Demand Forecasting	Baseline Assessment Using WSEF	Demand Forecasting and Climate Resilience Assessment
2	Identify Potential Future Deficits	Identify At-Risk Zones	Risk Identification
3	Problem Characterisation	Investment Need Identification	Supply Resilience Modelling
4	Option Identification	Option Development	Option Identification and Feasibility
5	Option Appraisal	Integration into Investment Planning	Stakeholder Consultation
6	Preferred and Adaptive Plan Selection	Preferred and Adaptive Plan Selection	Public Consultation
7	Public Consultation	Public Consultation	Revised Plan
8	Revised Plan	Revised Plan	Public Consultation
9	Public Consultation	Public Consultation	Final Plan
10	Final Plan	Final Plan	

Water undertakers face different imperatives and challenges in maintaining water resource sufficiency and resilience. Water undertakers in areas where impermeable geology is dominant, such as the North of England, are more vulnerable to short-term droughts but can recover from droughts more quickly (Environment Agency, 2024). Whereas water undertakers in areas that are dominated by groundwater are more vulnerable to multi-season droughts, in particular to successive dry winters when groundwater would otherwise be expected to recharge. Groundwater provides a buffer to short droughts through supporting river flows, but it takes longer for groundwater to recover. Due to these differences the specifics of how water resource sufficiency and resilience is planned for differs and any metrics used must take this into consideration. In regions that are reliant upon desalination, there again are different considerations taken into account when planning (Shahabi, et al., 2017; Zolghadr-Asli, et al., 2023).

A core component of developing a WRMP in England and Wales is the identification of target headroom, which is the volume of water above estimated plan that should be planned for (Environment Agency, 2023). The target headroom acts as a buffer to account for uncertainties and further strengthens water resource security for supply. Where certain components are excluded from target headroom, it is essential to provide a clear explanation of the underlying assumptions and methodologies, ensuring that uncertainties are neither double counted nor omitted (Environment Agency, 2023). This methodology typically assumes that uncertainty components are independent. However, where interdependencies exist, risk modelling techniques are used to incorporate correlated or dependent factors into the headroom calculation, thereby improving the robustness and realism of the planning process (Smith et al., 2021).

The target headroom calculation provides a technical quantitative buffer specifically designed to management uncertainty in water supply and demand at the operational level (Environment Agency, 2024). This contrasts to national targets set in other European countries, such as France, where quantitative 'buffer' values may be set at a policy or target level rather than through a technical assessment of operational area (UNECE, 2025). Another example of a European approach is the setting of climate-sensitive targets, such as Montenegro who take an integrated river basin management approach to water management, where risk-based approaches that are often broader than the UK target headroom, incorporating climate vulnerability assessments and adaptation strategies across sectors (UNECE, 2025; World Bank, 2016).

6.1.2 Drought planning

Drought planning is a tool to enhance water supply system resilience during unforeseeable dry weather events and droughts (Environment Agency, 2021; German Development Institute, 2017; Australian Government, 2024b), and has not been included within this study. While this study has focused upon water resource planning, we do note that drought planning is a standard approach across many countries particularly developed countries and the West. Within drought planning levels of service are specified. These typically relate to a drought or dry weather event of a specified return period (e.g. 1 in 10 year). These levels of service and the resilience actions associated with them are typically included within water resource planning through modelling. The demand savings of demand restrictions such as temporary use bans, and the increase in source availability such as use of strategic sources, are accounted for within the water resource model used to assess the deployable output within a defined drought scenario.

The definition of such a drought/dry weather event will change throughout time as weather and frequency of specific weather events changes. To measure resilience for such events, the chosen level of service measure(s) and corresponding acceptable limit(s) must be specified, e.g., for unusual supply restrictions due to drought (UKWIR, 2017);

- Resistance: Factors affecting probability of storage or flow issues and volume of usable water
- Reliability: Factors that affect outages and Water Available For Use (WAFU)
- Redundancy: Factors affecting headroom
- Response and recovery: Factors affecting effectiveness of drought intervention plans

The complex connections between the environment, agriculture practices and energy security with the quality and availability of water create vulnerability. Research indicates that water resilience could be improved through a wider assessment of water resource management. English water resource managers have started using the national water resource framework which includes cross-section cooperation and regional planning (Ward & Wentworth, 2021).

There is a significant focus on water quantity within water resource planning, however, there are some water quality limitations that should be considered. To preserve quality from pollution (usually from human activity) safety protection zones exist under EU framework such as nitrate vulnerable zone (Nitrates Directive) and safeguard zones (implemented under Water Framework Directive) (Ward & Wentworth, 2021). In the UK there are increasing requirements to consider raw water quality limitations to water resource availability in a WRMP context (Hall, et al., 2019; Penuela, et al., 2020; Ofwat, EA & NRW, 2023). For example, Gosling et. al. (2024) outline how climate change is increasing the risk of water scarcity in Scotland, including its impact on water quality. They conclude that new BAU weather patterns need to be planned for, and the parameters considered in water resource planning adjusted to reflect changes in climate (i.e. a risk-based approach).

6.1.3 Balancing sufficiency of supply with the need to maintain environmental flows and a changing water environment

Integrated and multi-scale water resources planning is increasingly being seen as critical for managing complex water systems. For example, in Arizona, water resources are assessed at basin, state, planning area, and local planning scales to align WRPM goals with the local needs at each level (Hwang, 2018). Environmental flows are an important consideration in this context which has increased the complexity of planning. The value of environmental flows extends beyond environmental protection to securing long-term water availability for major users and investors (Dyson, et al., 2003).

Hydrological models have improved reliability estimates for water storage and supply by accounting for hydrologic variability (Salazar & Wurbs, 2002). More recent models, such as stochastic resilience optimisation tools also provide strategies for determining environmental flows from storage systems while maintaining a specified level of resilience and risk (Chu, et al., 2018).

Effective water governance must also support vulnerable populations and local livelihoods. For example, in China, integrated approaches to environmental flows assessment manage trade-offs between environmental risks and supply security (Gippel, et al., 2010). However, issues can still arise when water allocation frameworks fail to prioritise environmental protection or account for high-flow events which can be essential to ecosystem health (Ritcher, 2009). As a result, it has been argued that environmental flows should be managed similarly to water quality, through regulation of land and water use activities, rather than treated as allocations (Ritcher, 2009).

6.2 Key Performance Indicators

6.2.1 SoSI and SDBI

A key UK metric (now replaced) was the Security of Supply Index (SoSI). This identified the security (resilience and sufficiency) of supply through a score out of 100 (Ofwat, 2011). For each point a water company scored below 100 a financial penalty could be triggered, but once the score dropped below 97 the financial penalty didn't increase. The SoSI score calculation included data on water available for supply, distribution input, headroom, target headroom and population.

SoSI was retired and replaced with the Supply Demand Balance index (SDBI) metric (Office for Environmental Protection, 2025) from reporting year 2021. While no explicit rationale for this change has been identified in publicly available evidence, in UKWIR's (2017) report they conclude that SoSI was a relatively good indicator of customer outcomes but is one step removed. They also state that the metric may be challenging for customers to understand, these conclusions may have contributed to the retirement of this metric.

SDBI measures how the actual supply demand balance has performed compared to what is set out in a water company's WRMP (Environment Agency, 2020). The SDBI is an assessment of how actual supply demand balance has performed against the design event in relevant company WRMP is based upon. SDBI is scored out of 100 as part of the Environmental Performance Assessment by the Environment Agency. The expected performance is for water companies to have a SDBI of 100. If a figure below 100 is reached, the water company must describe actions it is taking to improve its performance as security of supply is at risk. Water companies are expected to provide a short commentary on each component of the calculation (see Appendix D) to explain how it has been calculated and show any differences from their WRMP. Companies have been required to report SDBI since FY21, and up to FY24 an overall increase of 0.4% has been calculated across the three datapoints (Office for Environmental Protection, 2025). However, since SoSI and SDBI are not comparable and companies have been required to report SDBI for a single AMP so far (Office for Environmental Protection, 2025), this has not provided sufficient time to evaluate the effectiveness of this metric upon water supply sufficiency and reliability.

6.2.2 Reservoir system performance

According to Hashimoto et al. (1982, via (Xefide & Ophori, 2009)), resilience for a reservoir is defined as the likelihood that a reservoir system recovers after a failure. It is calculated using Equation 1, which incorporates both the frequency and duration of failures. Longer average failure durations result in lower resilience, whether due to extended individual failures or fewer recovery events, indicating a greater difficulty for the reservoir to recover.

Equation 1 Reservoir resilience (Xefide & Ophori, 2009)

$$\varphi = \frac{1}{f_d/f_s}$$

Where:

- φ is resilience.
- f_d is the total duration of failures.
- f_s is the number of individual continuous sequence of failure periods.

Reservoir vulnerability can also be calculated, it quantifies how severely a reservoir fails to meet a specified target draft (Xefide & Ophori, 2009). It represents the average volume by which supply falls short during failure periods.

6.2.3 Water security indices

Water security is most often evaluated at national level. As such, many of these metrics have been developed based on data which is available at a national level, such as that reported by governments to UN bodies. Limited use was found for using these indices at a localised level. This is also true of national-level resilience frameworks such as the OECD fragility framework (OECD, 2025). Water scarcity metrics typically consider aspects such as average per capita water availability, water-related risk, access to water, provision of water to support ecosystem services, and institutional capacity to realise the requirements (Mason, 2013).

In addition, there is a growing academic opinion that water security needs to be assessed in dynamic terms. Krueger et al suggest that the solution is to consider system resilience (ability to recover) instead of security (ability to withstand events) in order to respond to shocks which are dependent on their timing and magnitude, requiring constant adaptive management (Krueger, et al., 2019). The need for dynamic resilience was also expressed by WRF who suggested that dealing with exceptional circumstances "*can place too much emphasis on preserving the status quo of the system (a return to 'normal') and can stand in the way of broader system improvements and innovations*" (Water Research Foundation, 2018).

6.2.4 Water situation reporting

Water companies complete their own water situation reporting, in addition to the water situation reporting undertaken by the Environment Agency. Water situation reporting typically occurs in England monthly (Environment Agency, 2025), with the situation report for each month being published by midway through the next month once all data has been collated, processed and analysed. Within these reports there are metrics to communicate the water situation such as:

- Total monthly rainfall (as mm, as % of long-term average (LTA), and as per category)

- Total 3 month rainfall (as per category)

- Total 6 month rainfall (as per category)
- Total 12 month rainfall (as per category)
- Groundwater level category (as per category, and level mAOD)
- River flow category (as per category, and flow in m^3/s)
- Monthly rainfall above / below monthly LTA, for past 12 months (as %)
- Monthly effective rainfall above / below monthly LTA, for past 12 months (as %)
- Soil moisture deficit (as mm)
- Reservoir (as % of live capacity)

Where unit is ‘per category’, the categories are based on historical data (time period variable, specified in water situation charts) and percentiles (Environment Agency, 2025):

- **Exceptionally High**: Value likely to fall within this band 5% of the time.
- **Notably High**: Value likely to fall within this band 8% of the time.
- **Above Normal**: Value likely to fall within this band 15% of the time.
- **Normal**: Value likely to fall within this band 44% of the time.
- **Below Normal**: Value likely to fall within this band 15% of the time.
- **Notably Low**: Value likely to fall within this band 8% of the time.
- **Exceptionally Low**: Value likely to fall within this band 5% of the time.

We did not find evidence of monthly publicly available water situation reports, outside the UK. However, the US, for example, publishes the National Water Availability Assessment Report which provide synthesis and interpretation of water availability in the past, present, and future (Stets, et al., 2025), and water statistics are published for countries in the EU (Eurostat, 2024).

6.2.5 Additional metrics and considerations

The UK Water and Wastewater Resilience Action Group (WWRAG) established a Task and Finish team on resilience metrics in late 2016 (UKWIR, 2017). This cross-sector team developed a set of initial resilience metrics across water supply, wastewater, asset health and the environment. The key criteria the group used were to develop metrics which were forward-looking, could be applied consistently and would be meaningful for customers. They identified that the most obvious unit for the metric is WRZ, and that metrics for water supply resilience that included population served by isolated supply systems (% population) and Number of degraded catchments/sources (% DO affected). Additional metrics were included for raw water, but these typically focused on resilience during drought, which is not included within the scope of this project.

6.3 Operational Metrics

6.3.1 Water resources risk assessment

Water resources risk assessments (WRRA) can be undertaken in various ways and are often undertaken as part of drought planning and management. In the UK these assessments are likely to be undertaken internally for company information, potentially as part of their internal water situation reporting, therefore methods of assessment may not be publicly available.

The specific methodology for WRRA likely vary between water company based on the water resource characteristics (as discussed in Section 6.1.1). It can incorporate a range of data such as of hydrological data, groundwater levels and predicted groundwater levels, predictions of drought impact and assessment of potential drought severity in terms of historical frequency of occurrence (Thames Water, 2022; South East Water, 2022). Although unforeseen events such as droughts are excluded from this project's scope, WRRAs in relation to drought planning and management can be part of BAU for a UK water company to monitor the water situation and identify potential for a dry weather event or drought to occur at the earliest opportunity.

6.3.2 Catchment risk scores from Drinking Water Safety Plans

Water treatment works treat water within a certain water quality envelope to a required drinking water quality standard. Occasionally raw water quality falls outside this operational envelope and it can impair treatment performance or pose risks to treatment and/or distribution assets, as well as output water quality. In such cases, the availability of treatable raw water is constrained, which reduces water supply sufficiency and reliability. Some of these issues are captured within a Drinking Water Safety Plan (DWSP), however, limitations related to assets such as wanting water of a certain turbidity to reduce siltation of raw water reservoirs, may not be captured. Metrics linked with catchment management or protection may be beneficial in some circumstances to increase water supply resilience and security (Hunt, et al., 2017).

Additionally, water quality issues in raw water reservoirs, such as algal blooms, can cause significant impact to raw water security. These issues are often captured through metrics relating to asset outages (Hunt, et al., 2017; Xefide & Ophori, 2009).

7. Resilience and sufficiency in water treatment

7.1 Approaches

Resilience and sufficiency in water treatment needs to consider the current and future robustness and reliability of assets and the redundancy to be able to meet demand or the required level of service under changes to [output] demand and [input] supply conditions or asset availability. This is complicated by the fact that treatment works operating capacity and performance is intrinsically linked to source water quality. For example, it is suggested that treatment potential of a WTP might typically reduce by 10% during high rainfall events (above the monthly rainfall average) due to the reduced quality of the raw water (Amarasinghe, 2014), although this will primarily impact works fed from surface water sources.

Redundancy is a common resilience approach taken for at a system level for wastewater treatment, for example diversity in water and power sources and multiple works with the ability to supply customers. Indeed, UKWIR found that the most common non-WRMP resilience commitment was that customers should be able to be supplied by more than one treatment works (UKWIR, 2017). However, this is not always a practical solution, particularly for smaller water supply systems where economies of scale mean that single larger works are more cost effective (Carstens, n.d.). Other common approaches include ensuring headroom to deal with demand fluctuations and demand changes over time and proactive maintenance to improve reliability.

7.2 Key Performance Indicators

7.2.1 Expected availability

‘Availability’, the percentage of time that service levels are being, or expect to be, met under current and future climate conditions is provided as an example resilience metric for measuring robustness within AWWA J100. It suggests that low might relate to <80%, medium 80-99%, and high >99%., but that levels of service should be mutually agreed between utilities and stakeholders. This extends the concepts of operational availability / maintenance-based metrics of reliability to a probabilistic, leading indicator of robustness.

7.2.2 Works with inadequate access arrangements

7.2.3 SEMD compliance

To be compliant with SEMD, water companies must provide a statement of compliance annually to DWI confirming they adhere to their obligations, including that all facilities and processes required for compliance are operational. Treatment plants, reservoirs and pipelines would also be classified as critical national infrastructure (Planning Inspectorate, 2024) requiring annual audits to assess physical and cyber security and contingency plans for compliance for operations and control (UKWIR, 2017). Timeliness, accuracy and completeness of submissions could be used as a metric of resilience. The DWI could also introduce additional requirements into this existing reporting mechanism.

7.2.4 Population serviced by critical works

This metric would require definition of a ‘critical’ works, which could be works which are sole source of supply to customers or isolated supply systems. The chosen definition would need to be clear and remove subjectivity to allow comparison and benchmarking. The calculation of the metric should also take into account common mitigation strategies that are used to reduce the risk from these critical assets so that companies are not punished for risks that have been mitigated by other means (UKWIR, 2017).

However, there are many risk components and contingent actions which together define whether a works is critical. Other examples include access to spare parts and access to skilled personnel which all could be considered as a leading indicator of service resilience as they affect the efficiency and effectiveness of incident response and recovery. Other examples include access to spare parts, access to skilled personnel and inadequate access to assets and sites, all which all could be considered as a leading indicator of service resilience as they affect the efficiency and effectiveness of incident response and recovery. This sort of metric would only provide a useful indicator of customer experience if it were linked to the risk to supply. For example, inadequate access to a component or site which has high levels of redundancy would be unlikely to affect customers’ level of service.

7.2.5 Unplanned Maintenance

The *Unplanned Maintenance* metric proposed by WWRAG tracks unplanned maintenance as an indicator of asset reliability. A similar metric was previously trialled during AMP5 but discontinued due to consistency issues. The WWRAG metric aims to provide a straightforward measure of the reliability of M&E non-infrastructure assets, such as trunk mains, treatment works and pumping stations. However, it could also be applied to other above ground non-infrastructure assets like the original Ofwat metric which calculated the difference between maximum sustainable production capacity and current available production capacity and weighted this by the number of days the outage lasted for each source works[16] It should be considered how well customer maintenance correlates with outages and customer impact and whether there would be overlap between this metric and existing asset health metrics (UKWIR, 2017; Ofwat, 2017).

[16] “*all assets used between and including the point of first abstraction and the point at which water is first fit for purpose (where it enters the distribution network)*”

Rather than the Ofwat approach, WWRAG suggests the metric is simply as the annual count of unplanned maintenance jobs. The main limitation lies in its technical application; specifically, the challenge of ensuring consistency and comparability of the data across years and between companies.

The metric is linked to the large-scale service disruptions caused by asset failures. It is assessed at a company-wide level and calculated as total number of unplanned maintenance activities recorded annually. Only jobs related to resilience-critical assets should be included, with clear definitions to exclude irrelevant or duplicate tasks and to distinguish between planned and unplanned events. It is also similar to the '*Hours reactive maintenance relative to total maintenance'* (see 7.3), acting as a reporting vehicle for the absolute number of reactive hours spent. While the normalised operational metric is more useful for comparing between plants, this metric is more useful for tracking performance at a single site over time.

7.3 Operational metrics

7.3.1 Historic non-availability

The non-availability of assets / plants / treatment processes is a common internal metric measuring the proportion of time the measured asset is out of production / isolated / fails to meet a minimum throughput threshold. It can be internally benchmarked against 'good' performance assessed from historical performance of the assets / similar assets. It is a lagging indicator, but the trend in non-availability can be used as a leading indicator of asset health.

7.3.2 Trend in Compliance Risk Index

The Compliance Risk Index (CRI) is an existing regulatory performance measure used by DWI to assess the risk to consumers arising from treated water compliance failures by water companies in England and Wales. It is reported annually to Ofwat. It is designed to reflect not just the frequency of compliance failures, but also their significance, management, and impact, aligning with a risk-based approach to water quality regulation. The CRI is calculated for every individual compliance failure at three key locations:

- Water supply zones (parameter score x assessment score x population affected, divided by the total population served)
- Supply points and treatment works (parameter score x assessment score x volume supplied (m^3/day), divided by the total daily volume supplied)
- Potable water storage (parameter score x assessment score x reservoir capacity (m^3), divided by the total potable water storage capacity).

By looking at the trend in CRI over time an understanding can be gained of whether a network is becoming more or less resilient to water quality incidents. An appropriate averaging period may be 3-5 years (e.g. trend is decreasing, increasing or stable over this period). Limitations of this metric include:

- It is a lagging measure (exacerbated by the use of a time average)
- It relies on sufficient data being available to perform a useful trend analysis
- It relies on good analysis of individual incidents
- Incidents are relatively rare which necessitates time-averaging to smooth out the trend. Isolated incidents could still affect the trend.

7.3.3 Hours reactive maintenance relative to total maintenance hours

Relative to a baseline which excludes incidents (operating outside of operational envelope or major compliance issues), this metric calculates the proportion of maintenance time which is reactive (in response to a failure). This is a current indicator of asset health and is often considered to be a proxy for resource availability (ability to resist outages and restore supply) with lower values indicating more robust (proactively maintained) system. (Hurley, et al., 2000)

7.3.4 Number of critical alarms / number of alarm points per time period

Relative to a baseline which excludes incidents (operating outside of operational envelope or major compliance issues), this metric calculates the either the proportion of alarms that require significant intervention in order to prevent a loss of supply or the occurrence of such alarms over time. A high value of this metric suggests poor asset health. This is a lagging indicator of asset health.

7.3.5 Number of sub-threshold alarms / number of alarm points per time period

Relative to a baseline which excludes incidents (operating outside of operational envelope or major compliance issues), this metric calculates the either the proportion of alarms that require (any) intervention in order to prevent a loss of supply or other non-compliance, or the occurrence of such alarms over time. A high value of this metric suggests deteriorating asset health. This is a leading indicator of asset health.

7.3.6 Cumulative sum final water turbidity or similar SPC trend

Relative to a baseline which excludes incidents (operating outside of operational envelope or major compliance issues), this metric calculates the cusum (cumulative sum) trend of final water turbidity (or similar statistical process control indicator). The trend over a calendar year should be negligible (although seasonal variation would be observed), for example ±0.1 NTU/year. This is not generally used to assess resilience but could be used as a leading indicator of medium-term performance drift.

7.3.7 Post-clarification turbidity (absolute value of headroom to target)

Relative to an internal sub-threshold value (or e.g. 1 NTU), this metric is an indicator of primary treatment stage effectiveness which will indicate resistance to changes in inlet water quality which could impact final compliance. This could be used as a short to medium-term leading indicator of performance headroom.

7.3.8 Trend in nominal clean bed headloss

Relative to a baseline which excludes incidents (operating outside of operational envelope or major compliance issues) this metric measures backwash efficiency. The trend should be negligible (less than, say 0.5 mm/month). This could be used as a leading indicator of short to medium-term performance drift in filtration system performance.

7.3.9 Number of unplanned process shutdowns

This metric would count the number of whole works streams that are unavailable for any period of time (UKWIR, 2017). A clear definition would be required with consideration given to whether there should be a threshold time below which a shutdown is not counted (or above which a continued shutdown is recounted).

8. Resilience and sufficiency in strategic water distribution and potable water storage

8.1 Approaches

Approaches to assessing sufficiency and resilience in trunk distribution include defining criticality at an asset level or at a system level. Portsmouth Water take a system level approach considering the impact of each single point of failure during peak and average demand conditions to assess "*both multiple knock-on/cascading impacts and unrelated multiple failures across all operational assets*" (Portsmouth Water, 2019). Examples of an asset level approach is that taken by Welsh Water who keep a register of their most critical assets, tracking their performance over time and measuring their tolerance to risks (UKWIR, 2017) and the regulatory setup in the Netherlands where assets are categorised according to their criticality where:

a) "*a level 1 breakdown should never occur, as it would significantly disrupt service (defined as providing service to >1000 households or a hospital or firefighting)*

b) *a level 2 breakdown is allowed to occur every 3 years,*

c) *a level 3 breakdown is acceptable once a year because it is not vital to operations*" (Stip, et al., 2019)

Different maintenance and redundancy requirements are then set according to the categorisation, for example, storing spare parts would be suitable for assets associated with level 3 failures, while those related to level 1 would require regular inspection (Stip, et al., 2019).

8.2 Key Performance Indicators

8.2.1 Design storage

The resilience of storage to demand shocks can be measured according to the storage capacity compared to the demand on the reservoir. For example, South African design guidelines (Red Book) specify that the storage reservoir should have a storage capacity of 48 hours of annual average daily demand (AADD), while the capacity of the supply mains to the reservoir should not be less than 1.5 times AADD for the area served by the reservoir. Chang's thesis challenged this guidance. By using stochastic modelling to consider failure frequency under different scenarios (with no consideration of future growth) he finds the supply capacity to be insufficient to achieve reliability more than the target value of 0.1 failures/annum under seasonal peak flow. Chang also advocates defining reliability of a water system in terms of the reliability of its storage. He suggests that the metric should be frequency of reservoir failures as opposed to duration of failures (Chang & E. van Zyl, 2014).

Portsmouth Water, for example, demonstrate resilience to Ofwat by claiming that they hold, on average, 48 hours of potable water storage, twice the amount that is considered as resilient by some practitioners in the UK (Portsmouth Water, 2019). Other international examples of how sufficient reservoir design storage can be stipulated include France where balancing storage of 30% of peak day demand is required in addition to 120 m^3 for fire protection and 2 average days of emergency storage and the UKA where 35% of peak day balancing storage is required plus 680 m^3 for firefighting and emergency storage of 1 peak day[17] (Ernst Van Zyl, et al., 2007).

Similarly, the Alberta Guidelines for municipal waterworks states that the water storage requirement for a water supply system should be equal to the sum of fire storage, equalisation storage (approximately 25% of projected maximum daily design flow), and the greater of emergency storage (minimum of 15% of projected average daily design flow) or disinfection contact time (T 10) storage.

8.2.2 Population served by critical potable water storage/trunk mains

Similar to population served by critical works, 'critical' could mean, for example, single feed (number of customers fed from a single source of water) or undersized trunk mains or storage with insufficient headroom. Inaccessible/vulnerable assets would also be relevant for trunk mains, or, for reservoirs, whether the population served by a reservoir stage is less than a threshold percentage of peak demand. As for treatment, the metric should consider whether operational workarounds are in place which can respond within the timescale of an event (before customers impacted).

8.2.3 Population served by isolated supply systems

Population Served by Isolated Supply Systems is an advancement to 'population served by critical potable water storage/trunk main' proposed by WWRAG as a resilience-focused metric that captures the percentage of population served by vulnerable supply systems; those reliant on a single raw water source or treatment works without available backup. This metric highlights both localised drought vulnerability and the risk of large-scale supply interruptions, especially in systems that cannot mitigate threats such as drought, pollution, flooding, or malicious incidents through network connectivity or resource sharing.

Achieving good practice relies on clearly defining what constitutes an "isolated" system, which may include those with no alternative connections or very limited transfer capability. The definition should also address potential exclusions, such as large treatment works with redundant processes or storage that provide sufficient protection, to ensure the metric remains relevant and actionable.

[17] Design criteria for low density residential areas

The service disruption considered involves supply loss or abnormal restrictions due to the inability of isolated systems to compensate under stress conditions. The scale of assessment applies at the supply system level, such as water resource zone or water supply zone.

The metric is calculated as the percentage of the population served by systems that meet the defined isolation criteria. Clear definitions and potential improvement pathways (example, infrastructure upgrades or interconnections) are important to ensure comparability and support long term planning.

A simpler version of this metric is the proportion of customers supplied by at least two separate sources.

8.2.4 Capital schemes delivered

A surrogate for future resilience (leading indicator) is investment in resilience schemes, for example, potable water storage expansion, duplication, trunk main replacement (length of new trunk mains) or investment in enhanced/real time monitoring. However, this metric has the limitation that it is hard to measure the impact of the investment on resilience and hard to ensure that the right investment choices were made. Capital spend should also not be encouraged if operational solutions would be more cost effective.

8.2.5 Unplanned Maintenance

See section 7.2.5.

8.2.6 SEMD compliance

See section 7.2.3.

8.2.7 Proportion of customers fed from storage

Customer’s supplies which are connected directly to trunk mains or otherwise not connected to potable water storage are less resilient as the stored water is unable to continue supply when upstream issues occur. The proportion of customers fed from storage can be recorded as a resilience metric but has limitations that, often, no economic solution exists to supply these customers from storage.

8.3 Operational metrics

8.3.1 Trend in Compliance Risk Index

See section 7.3.2.

8.3.2 Non-availability

See section 7.3.7

8.3.3 Hours reactive maintenance relative to total maintenance hours

See section 7.3.3.

8.3.4 Number of critical alarms / number of alarm points per time period

See section 7.3.4.

8.3.5 Number of sub-threshold alarms / number of alarm points per time period

See section 7.3.5.

9. Resilience and sufficiency in local water distribution

9.1 Approaches

This section shall discuss methods of measuring and ensuring resilience and sufficiency of end water supply to the customer. In particular, this includes measurement of 'business as usual' level of service such as flow and pressure and measurement of the impact of disruptions which might have been caused by and anticipated by failures upstream As discussed in section 3 there is significant variation in the involvement of regulators in incidents. For example, in jurisdictions like the New Zealand and the Netherlands there are requirements for regulators to be informed about interruptions longer than a threshold criteria.

9.2 Key Performance Indicators

9.2.1 Supply interruptions

This metric might be phrased as 'average minutes lost' or a target of e.g. less than 1 day disruption per 1000 population per year. The number of incidents could also be counted to give the frequency of interruption. The former approach is currently used by Ofwat and has the limitation that consequence is not considered – the impact of a small number of customers experiencing frequent or long-running interruptions is likely to be more than a larger number of customers experiencing shorter outages. Timing can also affect consequence and impact. For example, it has been seen in section 3 that some jurisdictions take account of the time of day when setting the definition of interruptions or the required response. This has limitations as it cannot be known whether households or businesses require water during the night (although this could be included in the priority services register for vulnerable customers) but may overall give a more representative view of the impact of disruptions (e.g. minutes lost could be weighted according to average demand, with more weight given to disruption which occurs when customers are more likely to be needing water). When considering days of disruption per year it is likely to be most useful to define a threshold which defines an interruption (e.g. >30 minutes) and count the number of days where people experienced at least one interruption. This again has the limitation that it does not consider the impact of the disruption, how long it lasts, or whether the interruptions are focussed on a small group of unfortunate customers.

The current supply interruptions metric in England and Wales is average customer minutes lost per property per year due to supply interruptions of three hours or more. Both planned and unplanned interruptions are reported. In Northern Ireland data is reported for over 3 hours, over 6 hours, over 12 hours and over 24 hours. This does not consider the impact on non-households.

9.2.2 Number of properties at risk of loss of supply from failure of a single source of supply

By way of example, Portsmouth Water reported to Ofwat in their PR19 resilience action plan that (Portsmouth Water, 2019)

- No properties are at risk of loss of supply from a single source of supply failure on an average demand day.
- 100,000 properties are at risk of loss of supply, for a proportion of the day, from a single source of supply failure on a peak demand day.
- 44 properties fed via boosters are at risk of loss of supply from a single source of failure on an average and peak day

These metrics directly measure customer impact but do not take into account other forms of risk mitigation or the challenges of remediating the situation in these properties.

A similar metric, number of customers fed from isolated supply systems, was discussed by (UKWIR, 2017). They suggested that the metric was a useful reflection of both localised drought risk and the risk of large-scale interruptions and that it could be defined based on a criteria such as no connections to other parts of the water system or where transfer capability is less than a percentage of demand.

9.2.3 Emergency preparedness

Metrics to assess emergency preparedness might improve

- Adequacy of staff training (UKWIR, 2017)
- An assessment of response plans (UKWIR, 2017)
- Measure of how up to date plans are
- Ability to provide alternative supplies beyond SEMD minimum (UKWIR, 2017)
- Coverage of real time monitoring / early warning systems

9.2.4 Population at Risk from Large Scale Interruptions

The *Population at Risk from Large Scale Interruptions* proposed by WWRAG and (UKWIR, 2017) outlines two proposed metrics for assessing population risk from large-scale, high-impact, low-likelihood (HILL) water supply interruptions.

Their objective was to create metrics that are both technically robust and understandable to customers. The first is a quantified risk metric, which estimates the expected number of customers affected annually using a probabilistic ‘likelihood x consequence’ model. While this approach aligns well with customer valuation methods like willingness-to-pay, it relies on subjective data and uncertain assumptions. The second is a criteria-based metric, which identifies systems with unacceptable risk-based factors like lack of redundancy, vulnerability to hazards, and potential scale of impact. This method is more technically defensible but requires strong customer engagement to ensure relevance and support.

Disruptions considered by these metrics involve extended service loss and large customer impact, making them suitable for application at the water supply zone level. The quantified risk metric is calculated by summing the expected impact across critical systems, while the criteria-based metric counts the number of customers served by vulnerable systems.

The first metric reports the expected number of customers affected per year:

*Quantified risk metric: sum risk (likelihood * number of customers affected) for all critical systems meeting the criteria*

while the second gives the number of customers serves by high-risk systems:

Criterial metric: number of customers served by system which has meets criteria, e.g. no redundancy, non-trivial risk, threshold number of customers affected

Both aim to highlight areas for investment and resilience improvement.

Advantages are that water companies already have the data to report this metric and that there could be industry benchmarking with a common target. Limitations include

- overlap with the existing >3 h interruption metric
- it does not address longer-term threats which are not significantly impacting performance presently. This could be particularly problematic is performance commitments result in double jeopardy or double reward for investment
- Criteria metric is potentially too ‘one size fits all’ and incentivises only meeting the criteria rather than continuous improvement and minimising risk
- Quantified risk metric tends to overestimate risk as it does not consider the ability to rezone or storage.

9.2.5 SEMD compliance

See section 7.1.

9.2.6 Minimum supply pressure/flow

Sufficiency to customers is usually defined in terms of a requirement on the pressure and/or flow rate that customers receive. The point at which these criteria are specified and how they are measured and verified often vary and cause ambiguity, particularly when considering things like joint supplies. There is also confusion caused by standards and plumbing codes requiring minimum pressures at outlets within properties without an obvious consideration of the supply pressure. For example, a UK water company could be providing pressure above the GSS limit of 7 m under an allowable exclusion from DG2 (e.g. direct feed from a reservoir) which could never result in >10 m at all outlets in the property without installation of a pump. If 10 m head at outlets is defined by standards as sufficient, it could be argued water companies should be required to provide more than 10 m to the main stop tap (and without exclusions) in order that this requirement can be met by a reasonable design of internal plumbing. It should also be considered whether providing sufficient supply should include firefighting provisions. While this is not always a legal requirement, it could be within customer's expectations.

The requirements in the England and Wales are compared to select other countries and standards in Table 9.1.Table 9.1Table 9.1 Pressure requirements by different international standards and bodies

Country / standard	Pressure (metres head)	Flow / volume	Conditions	Exclusions
Netherlands (vewin, 2025)	15	1000	Pressure relative to ground level at point of delivery	"*When drinking water production is functioning as intended and there are no extreme conditions*"
Netherlands (vewin, 2025)	N/A	75% of peak day[18]	Under disrupted circumstances	Within 24 hours of disruption
Portugal (Portugese legislation, 1998`)	10	N/A	Firefighting provision	Measured at hydrants under single hydrant operation

[18] maximum amount of drinking water supplied as it has occurred on one day in the past ten years

Country / standard	Pressure (metres head)	Flow / volume	Conditions	Exclusions
Portugal (Portugese legislation, 1998`)	H=10+4n Where n = number of building stories However, there is also a requirement that pressure at usage devices in buildings >10 m	N/A		
New Zealand (Water Industry Commission for Scotland (consultancy), 2022)	10	9 l/min	At customer's side of the main stop tap and the customer's side of any meter or other fittings.	Similar to the UK 'DG2' standard there are exclusions for abnormal demand, planned maintenance, one-off events and alterations to the level of service for joint supplies
New Zealand (Wellington) (Wellington Water, 2024)	25		At point of supply	10 m "*may be accepted for highest properties adjacent to reservoir*"
BS EN 806-3:2006 (E)	Flow pressure: Minimum 10 at all draw-off points		There is a requirement to maintain pressure "across vertical zones". For example, maintaining sufficient residual pressure for upper floors after accounting for friction losses	Applicable to Austria, Belgium Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom
BS 750:2012	17	2000 l/s	Specification for underground fire hydrants	Under test conditions

Country / standard	Pressure (metres head)	Flow / volume	Conditions	Exclusions
BS 9990:2015	1.7	25 l/s	Specification for water supply at hydrants in buildings	
UK firefighting (HM Government, 2024) (Water UK, 2007)	"adequate"	8 l/s for housing up to 2 floors, varying by property type up to 75 l/s for large industrial/ commercial buildings		Can be provided by alternative means if there is insufficient pressure or flow in the water main
England and Wales GSS (Defra, 2024)	7	N/A	Payment required after 2 cases in 28 days	
England and Wales DG2 (Ofwat, 2017)	10	9 l/m	Customer's side of main stop tap (or a surrogate pressure of 15 m head at the adjacent distribution main) Joint supplies according to loading units in BS6700	Abnormal demand, unplanned events, proximity to reservoirs
UK WIA (UK Government, 1991)	"*at such a pressure as will cause the water to reach to the top of the top-most storey of every building within the undertaker's area*"	"constant supply"	Enforced by Ofwat through DG2	"necessary works"
Uniform Plumbing Code (USA) (IAPMO, 2024)	10 m	N/A	Pressure less than 10 m after accounting for internal losses is 'insufficient' and	

Country / standard	Pressure (metres head)	Flow / volume	Conditions	Exclusions
			requires a booster to be installed raising pressure above 15 m	
AS/NZ 3500.1	5 m and "*ideally pressure at outlets should not be less than*" 15 m	N/A	Within commercial or residential buildings	
	Minimum pressure downstream of an outlet shall not be less than 25 m Where water pressure is less than 10 m head of water at the final level on the building platform, a private boosting pump station may be permitted providing pressures compliant with the minimum and maximum pressures can be achieved at the point of supply. It is the designer's responsibility to demonstrate that the public network can supply the sprinkler system's flow and comply with all relevant standards		The minimum pressure shall be the pressure available immediately downstream of the point of supply when the property is continuously supp. The water supply network shall be capable of providing the minimum levels of service at peak demand	

9.2.7 Global Resilience Analysis-Based Benchmark Framework

The global resilience analysis-based framework is a methodology for assessing and comparing the performance of reliability indicators in water distribution systems. It suggests that a performance threshold (typically 80% of normal water supply) is used to define failure and that the time between an asset failure ('initial disturbance') and system failure is measured as the 'time to strain'. The duration of failure can also be measured alongside the rate of deterioration (known as failure rate in the framework and calculated as the time taken to go from the threshold value to the lowest observed performance of the metric within the incident), duration (time metric is below threshold), recovery rate (time to go from minimum back to threshold value), magnitude (difference between the threshold and minimum value of the metric) and severity (area of the performance curve below the threshold level). (Huang, et al., 2024)

The following operational metrics were compared in Huang's study: CERI, PHRI, REDU, NRI, DSFE. CERI was found to perform best followed by NRI, REDU, PHRI and DSFE.

9.2.8 Pumping station outages

Pumping station reliability can be measured through failure rate, mean time between failures, mean time to repair (time required to repair a failed pump or station), or the proportion of time station is available to deliver the required demand. However, as there will often be redundancy in pumping stations, while reliability tells you about asset health and risk (the likelihood of multiple pump failures increases as the reliability of individual pumps decreases and the capacity to cope with demand surges decreases when pumps are out of action), it is not generally a good measure of resilience on its own.

9.2.9 Redundancy

The number of standby pumps, alternative flow paths or other forms of redundancy, such as availability of box spares are often used to assess the resilience of pumping stations. Limitations of this approach can be that redundancy doesn't always mitigate against all hazards (e.g. standby pumps with the same power source during power outages).

9.2.10 Service reduction rate

A similar metric to the above is the service reduction rate, calculated as (minimum level of service at threshold pressure / full-service capacity)/(Threshold pressure/Design pressure -1)

This represents the rate of service reduction with reference to a pressure shock (increase in pressure). A higher rate of service reduction means low resilience as it shows low ability to absorb pressure (high sensitivity to= pressure) (Amarasinghe, 2014).

9.3 Operational metrics

9.3.1 Trend in Compliance Risk Index

See section 7.3.2.

9.3.2 Non-availability

See section 7.3.1.

9.3.3 Hours reactive maintenance relative to total maintenance hours

See section 7.3.3.

9.3.4 Number of critical alarms / number of alarm points per time period

See section 7.3.4.

9.3.5 Number of sub-threshold alarms / number of alarm points per time period

See section 7.3.5.

9.3.6 Hydraulic model metrics

A common approach to assessing water distribution sufficiency and resilience is to use hydraulic models. This allows resilience and sufficiency to be quantified by bottom-up indicators estimating customer levels of service, network capacity or network serviceability under current operation (digital twin) or hypothetical scenarios. These indicators typically require topological information such as node count and pipe count in addition to hydraulic information such as required demand, actual demand, head, pressure, flowrate, diameter, velocity, length, and head loss for each node/link. (Huang, et al., 2024) Appropriate use of such metrics could be used to demonstrate resilience thinking and supply sufficiency to the regulator. An overview of these metrics is provided in Appendix I.

10. Consumers

10.1 Approaches

10.1.1 Demand management

The role of demand management in ensuring resilience of supply should be considered. As discussed in section 1, a sufficient supply may be less than total demand on a water system (e.g. excluding non-domestic uses) and PCC in England and Wales is higher than is considered sufficient by bodies such as WHO. As such, it should be considered how demand can be managed, particularly during times and areas of water stress, in order to maintain an adequate level of service to all customers.

10.1.2 Water efficiency

PCC is generally a poor measure of water efficiency due to the impacts of leakage. Alternative approaches include consumer education, water efficient fittings, rainwater harvesting (such as installation of water butts), and leakage management. For example, water companies have previously measured their level of activity (provision of water saving devices), while one could equivalently measure investment, or impact. However, there could also be measurement of customer uptake and behavioural change (how are customers contributing to the resilience of their supply). The UK Government is now seeking the powers to bring in measures, such as labelling and minimum efficiency standards, through relevant clauses in the Environment Bill. (UK Parliament, 2021)

10.2 Key Performance Indicators

10.2.1 Usage restrictions

The frequency of usage restrictions can be used as a sufficiency metric. For example, (Howe, et al., 2018) defined a ‘standard annual shortage event’ (SASE). ‘A drought of sufficient severity and duration the residential outdoor water would be restricted to 3 hours every 3rd day for the months of July, August and September. System reliability can then be defined in terms of the frequency of occurrence of the event.

Some water companies set targets or report current performance regarding meeting customer demand within their WRMPs and Drought Plans. While Drought Plans are not in scope, usage restriction targets/commitments are provided in as this provides useful information regarding likelihood of water restrictions and, by implication, resilience of water distribution.

Table 10.1 Expected return periods (1 in x years) of water use restrictions from current WRMPs (2024-2029)

Water company	Temporary use ban	Non-essential use ban	Rota cuts/ standpipes/ emergency drought orders	Notes
Portsmouth Water	1:10	1:40	1:100*	
Anglian Water	1:10	1:40	1:100*	
Severn Trent Water	3:100	3:100	Unacceptable	
Dwr Cymru Welsh Water	1:20	1:40	Never	
Southern Water	1:10*	1:20*	1:200*	*Believe it will more likely be 1:4
Yorkshire Water	1:25	N/A	1:500*	
Affinity Water	1:10	1:40	Unacceptable beyond shorts periods of time*	
SES Water	1:10	1:20	1:200*	
Thames Water	1:10	N/A	N/A	
United Utilities	1:40	1:80	1:200*	
South West Water	1:20	1:40	1:200*	
Northumbrian Water	1:150	1:200	1:200*	
Bristol Water	1:15	1:33	1:500*	
Cambridge Water	1:10	1:50	1:100*	

*The National Framework for Water Resources requires water companies to plan for 1:500 drought resilience by 2040. (Environment Agency, 2020)

Examples of other commitments are Yorkshire Water's commitment that drought plans are to be updated every 5 years to reflect latest available information and innovations (Yorkshire Water, 2025) and Thames Water planning to protect an additional 20,000 customers from a 1 in 200-year drought by 2025 and all customers by 2030-31 (Thames Water, 2024).

10.2.2 Customer satisfaction

One way to assess whether customers are receiving a sufficient and resilient supply is to consider customer satisfaction with the level of service they receive. Common approaches include short survey questions that assess perceived components of water insecurity such as access, affordability, quality or quantity. (Stoler, et al., 2021)

The Household Water Insecurity Experiences (HWISE) scale was the first cross-culturally validated household-level metric. It was designed to measure customer experience in different contexts where there was a lack of water security. 12 items made up the original scale including disruption due to water availability, consumption, personal hygiene and psychosocial distress using a 4-week recall period. A 4-item shorter version was also created. More recently it was adapted to become the individual water insecurity experiences (IWISE) scale which was primarily used in health and development surveys. Stoler asserts that the metric "*has been deployed in more global settings than any other water metric due to its inclusion in the 2020 Gallup World Poll in 31 countries, a national-level sample of individuals who were not nested in households*" which aimed to produce national estimates of water insecurity. (Stoler, et al., 2021)

The authors note the limitation of this use case of aggregating responses over a year as this obscures the impact of fluctuations in water availability and lost precision by asking people to remember events from a long time ago.

The authors also note that "*frequency continues to be a generally accepted measure of resource insecurity, owing to commonly used food insecurity metrics such as the Household Food Insecurity Access Scale or the Food Insecurity Experience Scale. In such approaches, the severity of an item is assumed to be inversely related to experiential frequency within a population. But there is no compelling empirical evidence for this relationship*" (Stoler, et al., 2021).

10.2.3 Technical Resilience Navigator

The Technical Resilience Navigator (TRN), a tool developed by the U.S. Department of Energy's Federal Energy Management Program (FEMP). It is designed to help companies mitigate from disruption to water or energy services. This is not directly relevant to project aims but could be used by companies to promote resilience 'to tap', particularly for non-household customers. It may also have application in water treatment works or pumping stations. Each of the metrics is scored from Low to High (4-point scale) according to the extent to which the indicator has supported the energy/water resilience objective (Stoughton, et al., 2021).

Metrics cover:

- whether sites have an emergency plan which includes the operation of redundant energy and water systems and contains the established essential elements

- whether power demands can be met by off-grid sources
- whether the site has multiple electricity and water feeds
- Frequency of previous outages.

11. Discussion and concluding remarks

It is clear from the above review that there are several methods which are used to measure and ensure sufficiency and continuity of supply, or supply resilience more widely. These methods fall into one of 5 broad categories which are discussed below.

11.1 Asset approach

In an asset approach, resilience and sufficiency of the overall water supply system would be monitored by metrics which monitor the current serviceability and resilience to future shocks of critical assets . Suitable levels of sufficiency and resilience could then be ensured by requiring / incentivising water companies to meet targets. This approach is currently used in England and Wales for assets like pipes (e.g. measuring leakage and bursts).

Examples might include metrics assessing one or more of the following characteristics for each asset type:

11.1.1 Relevant to all assets

- Adaptability (future-proof design with suitable capacity for future growth and climate changes e.g. Canada).
- Performance headroom.
- Availability.
- Performance e.g. future risk of failure or historical failures.

11.1.2 Raw water storage

- Storage relative to demand and/or upstream supply under different demand scenarios.
- Degree of redundancy (multiple isolatable cells).

11.1.3 Treatment

- Self-sufficiency (stocks of chemicals, backup power etc.) (e.g. Netherlands).
- Adequate contingency plans.
- Degree of redundancy.

11.1.4 Potable water storage

- Water storage as a proportion of peak/average demand.
- Water quality – usable storage.

11.1.5 Distribution

- Minimum pressure and/or flow at peak demand.
- Asset health.
- Water quality.
- Pump redundancy / serviceability during pump outage.
- Alternative power supplies for pumps.
- Contingency plans.

11.2 Technical standards

An alternative to specifying asset performance/serviceability is to specify the resilience an asset / system must have rather than specifying how this should be achieved. Building upon the Local Government (Water Services) Bill in New Zealand (New Zealand Legislation, 2024), this might specify:

- The design life of assets and the requirement for whole-life costs or long-term asset management be achieved.
- Climate-resilient and future-proof design based on predicted impacts of climate and other changes on asset serviceability and health based on a specified future climate scenario and population growth scenario.
- Design using an adaptive pathways planning approach.
- Risk and resilience assessments outlining risks and what assets are at risk.
- Emergency response plans for asset failure for assets judged to be at risk or where consequences of failure are high.
- Headroom for development and growth.

- Sufficient capacity for flow and fireflow at a chosen demand level (e.g. Alberta, Canada).

This approach is taken in England and Wales for water resource planning (resource options are required to be sufficient up to a required demand in the future) and stormwater management (e.g. design storms).

11.3 Assurance approach

In an assurance approach the duty of the regulator to ensure resilience and sufficiency would be fulfilled by a requirement on the water companies to demonstrate resilience. The regulators would then be required to review this evidence of compliance. For example, this may include certification to, or compliance with, common standards by means of internal and/or external audit.

Assurance might cover aspects such as:

- Asset management and understanding of risk
- Emergency and contingency systems and plans
- Proactive maintenance and investment spend
- Incorporation of risk into decision making processes
- Monitoring of asset health, performance and capacity (operational metrics)
- Asset renewal and replacement plans
- Monitoring of hazards
- Demand and supply modelling.

11.4 Planning approach

Under a planning approach the duty of the regulator to ensure resilience and sufficiency would be fulfilled by a requirement on the water companies to demonstrate resilience through the creation of plans which have to be reviewed by a regulator. Such a system already exists in the UK for aspects such as business plans, DWSPs, WRMPs, regional water resources plans and drinking water quality proposals. This approach to resilience, also taken in USA, New Zealand and Japan, could extend the scope of regulatory scrutiny to include aspects such as:

- communication systems
- business continuity planning

- staff training
- vulnerability to insufficient supply
- emergency response plans, customer liaison and recovery plans
- demand forecasting.

DWSPs and Drought Plans potentially provide a ready-made mechanism to incorporate additional assurance around water system resilience into existing planning processes. For example, further clarity could be given to how future risks due to likely changes in demand and supply would affect risks in the DWSP, and how current demand variations would affect levels of service.

11.5 Hazards approach

Under a hazards approach the regulator would define a set of hazards which water companies must assess risk and demonstrate plans to mitigate. Examples include the cyber security management requirements in USA and Sydney, Australia. (Sydney Water, 2024)

11.6 Levels of service approach

Under a levels of service approach water companies are measured on the resilience and sufficiency of supply that is provided to the end customer, attempting to directly measure the quantities which the DWI are trying to ensure. Australia appears to be the most advanced at using this approach with many states providing target levels of service which utilities must meet (although there lacks yet full consistency across metrics and states and the levels of service themselves may fall short of UK expectations given typical exclusions and allowances for the effects of adverse weather). Setting target levels of service allow communities businesses and industries know what to expect, such as:

- Setting limits on frequency of water restrictions and how long they last (e.g. Australia)
- Defining a minimum volume per capita to be supplied or defining essential use (e.g. Australia, Italy, Belgium)
- Setting standards for industry or setting limit on total volume per capita rather than residential PCC
- Number of unplanned interruptions per customer per year / permitted frequency or length of unplanned interruptions or a reduction in unplanned interruptions (e.g. Australia, Norway)

- Requirement for communication / notice around planned interruptions (e.g. USA, Australia), e.g. any time there is a loss of supply for any period of time or an extended period of low pressure

The existing interruptions to supply and minimum pressure standards are examples of the levels of service approach being used to ensure sufficiency and continuity of supply in England and Wales.

11.7 Adopt a combined metric / resilience framework approach

There are a number of quantified approaches which aim to assess the overall resilience and sufficiency of water supply networks, such as those discussed in Appendix D. Under this approach, regulators could be assured of supply resilience and sufficiency by requiring performance above a particular level or a certain level of maturity according to the chosen approach. The CRI is an example of a combined metric being used in England and Wales which could be used to measure resilience of supply.

11.8 Concluding remarks

Without an agreed understanding of sufficiency, apart from the extreme minimum in the SEMD, there is a need for regulatory guidance on how one should comply with a sufficient wholesome water supply. We do not believe that all recommendations of WWRAG have been fully implemented. We also note disparity internationally regarding what is considered absolute minimum water supply (notably between the SEMD and WHO).

In addition, this review has shown that there is no single jurisdiction that provides a robust regulatory framework for ensuring customers receive a continuous and resilient supply. Sufficiency is not a defined term in the WIA. However, none of these are recommended alone as a template for implementation in England and Wales.

11.8.1 Comparing regulatory approaches for measuring resilience

Table 11.1 outlines some important advantages and disadvantages of the different approaches presented above. In isolation, each approach would not achieve all the DWI's aims. However, the subsections which follow suggest some implementation options which should be considered when developing regulatory guidance on measuring sufficiency and resilience of public water supply.

Table 11.1 Advantages and disadvantages of approaches to ensuring resilient and sufficient supply

Approach	Advantages	Disadvantages
Asset approach	• There is, at least relative to other approaches, little ambiguity regarding the interpretation and meaning of metrics.	• There will inevitably be level of service failures which are not picked up in the performance of metrics whichever metrics are chosen. • Poor asset performance may not result in customer service failure. • Measurement of specific quantities can have unintended consequences, particularly when there is an incentive to ‘move the dial’ on a metric rather than to fix the underlying issue. • Easier to measure resilience than sufficiency.
Technical standards	• Requirements are transparent, clear and under the control of the regulator. • These requirements can be directly linked to the levels of service and level of resilience the regulator wants companies to achieve. • Easier to enforce non-compliance.	• Assurance may be required to provide evidence to regulators that technical standards are being followed. • It may be hard to evidence compliance with these standards. • It may incentivise inefficient spend by imposing too many limitations on water company decision making or stifle innovation.
Planning	• The regulator is a stakeholder in water company decision making and can engage in dialogue with companies to manage trade-offs. • More cross-company consistency likely to be possible than by some other methods.	• Customers may not receive the intended level of service if assumptions in plans turn out to be incorrect. • Future planning takes precedence over operational resilience. • Regulator involvement is infrequent at plan renewal stage. Long lag before changes can be implemented.

Approach	Advantages	Disadvantages
	• Allows for bespoke solutions to be made, and targets set, for individual situations. • Regularly implementable using existing planning frameworks.	• Lack of ability to track impact and performance unless combined with indicators. • Focus of original plans could be lost or resilience and sufficiency objectives could become lost or watered down by competing priorities.
Hazards	• Expectations on companies are clear.	• Customers may not receive the intended level of service if threats materialise different to expected. • Water companies focus on meeting regulatory requirements rather than maximising resilience and customer experience.
Levels of service	• Direct measurement of the customer experience. • Well-established reporting route.	• Investment in short-term solutions may be incentivised over those which would be favoured by a planning approach or result in greatest long-term benefit. • Levels of service indicators are necessarily backwards looking so can de-incentivise forward planning. • Metrics tend to focus on historic performance and metrics will naturally be influenced by which threats materialise making metrics noisy and difficult to compare and benchmark. • It may not be cost-effective or affordable to achieve a specified level of service everywhere.

Approach	Advantages	Disadvantages
Combined metrics / frameworks	• Should allow for easy benchmarking and inter-company comparison. • Low effort for the regulator.	• Lacks transparency regarding the drivers of performance. • Trends and emerging risks can be obscured. • May insufficiently cover or weight the importance of different aspects to regulatory priorities and UK context. • Companies may be able to improve performance by focussing on some aspects to the detriment of others.

11.8.2 Properties of a good approach to ensuring sufficiency and continuity of supply

In order to build up examples of policy options, it is important to understand pitfalls that need to be avoided and clarify the objective. Following discussions with DWI, we can outline the following:

- The risk of volatility should be considered when considering use of direct outcome metrics for resilience as incidents are generally low probability but high impact.
- Resilience (avoidance of service failure) should not be confused with recovery and restoration (response to failure).
- There is risk associated with an asset approach as there is unlikely to be a one-size-fits all approach / hierarchy of importance across different zones, situations and geographical contexts.
- The DWI's remit should be focussed more on the outcome than the method, for example, specifying that operational metrics should be in place and monitored rather than specifying what they are.
- There is a preference for lead metrics and to provide suggestions as to what water companies should do to achieve a sufficient supply and metrics that could be used.

In addition, WRc propose the following:

- A suitable definition of sufficiency should be agreed. Unless supported by a willingness to pay argument, we believe that requiring water companies to meet peak day or peak hour demand is inefficient.
- Furthermore, the role of demand management should be considered. Strictly speaking, the duty of the water company is not to provide water to meet demand but to meet domestic consumption. There needs to be clear communication to customers about the level of service they should expect and their obligations. An approach like adaptive pricing would make it clearer to household customers what it considered to be sufficient supply and what is considered to be discretionary.
- While there are minimal obligations on water companies to meet non-household demand, the impact of disruption on industry and commerce should be considered. There should be an agreement about what level of service these water users should expect, and this should be clearly communicated.

11.8.3 Option 1: Process assurance

Certification to one or more standards, such as those listed in Appendix D, would provide assurance to DWI that water companies are following a consistent process and performing due diligence with respect to managing risks and their assets. The costs associated with formal certification and adoption of management systems should be considered. For example, it may be sufficient to mandate following the standard without requiring certification. This could be verified through investigation of failures or internal or external audits.

11.8.4 Option 2: Common risk and resilience framework

Adopting a common framework for assessing risk, resilience and sufficiency would be a step forward. By aligning definitions and approaches across companies and introducing consistency to reporting and monitoring the DWI will be able to start understanding current performance, identify gaps, and ensure progress towards the levels of service it demands. This approach was trialled by WRc in a collaborative research project looking at harmonising regulatory approaches to the assessment of customer service risk in distribution systems (Kowalski, M; Poole, K.; Purvey, A.; Garrow, D.; Glennie, E.; Hulance, J, 2011).

11.8.5 Option 3: Self-assessment to a resilience framework

The application of a resilience framework, perhaps alongside a combined resilience metric would allow water companies to self-assess risks to continuity and sufficiency or supply or supply resilience across their water network. This could then be reported to DWI and used to guide and prioritise investment in areas where risks are highest and resilience is lowest. This could also be combined with planning requirements relating to emergency response plans in areas with high consequences of interruption. Alternatively, this could be achieved through modelling resilience metrics under an agreed set of current and future climate and supply/demand scenarios.

11.8.6 Option 4: Level of service standards

Water companies could be assessed on how effectively they communicate information to customers about the level of service they are legally obliged to provide (water pressure, flow, volume, uses under business as usual, emergency supply, customer contact, notice and volumes of supply during abnormal conditions) so that customers know what they are entitled to.

The level of service that water companies are required to provide could also be further clarified, in particular regarding what is defined as sufficient water quantity in the long term (BAU) and what might be a sufficient supply of water for short periods of permissible outages (and, indeed, what outages may be considered permissible). This might amount to permitting outages for a maximum duration as long as sufficient warning is provided and the outage frequency for any given customer doesn’t exceed a threshold level.

Current levels of service requirements may be skewed towards household customers and domestic uses with less protection or clarity regarding what level of service can be expected by other water users.

11.8.7 Option 5: Systemic resilience measurement

Companies could be asked to demonstrate improvement in metrics over time to show that they are building resilience into their systems and adapting to emerging hazards. Metrics could be operational indicators such as unplanned maintenance or downtime or could be regulatory reporting metrics such as availability or population served by critical systems. However, direct metrics are likely to be more appropriate that outcome related metrics or level of service indicators which are not entirely within the water company’s control and will naturally drift over time due to changes in external factors. Alternatively, companies could be asked to demonstrate the effectiveness of proposed resilience spend or root cause analysis and resilience improvement following failures.

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Appendix A Assessing recommendations of the NIC

Table 12.1 Critical analysis of NIC report ‘Developing resilience standards in UK infrastructure’

Recommendation from NIC report	WRc comment
Peak demand: Government should consider a standard setting out the volume of water that water companies’ systems are required to be able to treat, store and put into supply over the course of a short peak demand period– as opposed to long term drought storage for which a standard already exists.	We consider this recommendation in section 1.4.3 We do not consider it to be reasonable, practical, or economical to expect water systems to be designed to supply peak day demand. However, designing systems to meet peak week demand may be more appropriate. In this situation, systems would likely to still to be able to provide water to the vast majority of customers under more extreme demand by depleting storage or providing water at a lower level of service. We interpret this recommendation to refer to distribution input.
Single source of supply: Government should consider a standard on the number of consumers reliant on a single asset for supplying their water.	We agree that the chosen standards should reflect, either directly or indirectly, critical assets which can loss of supply such as customers reliant on single sources of supply.
Forward looking asset health standard considering climate change related deterioration: The sector needs a forward-looking asset health metric which assesses the likely remaining life of assets, and the probability of failure over time, to ensure that resilience is not threatened by a failure to invest in long term maintenance or to address future threats .	We agree with the limitation of common asset health metrics which are backward looking. We have suggested metrics examining the trend / change in trend on operational / lagging indicators and considering the performance of metrics under future scenarios.
One in 50-year storm risk reduction target: Ofwat has guidance for companies on reporting on the percentage of customers at risk from a one in 50-year storm event – an event with a two per cent annual probability. Government should consider setting a desired risk reduction target in line with the Commission’s recommendation for a single joint target for surface water flood risk reduction.	We interpret this as relating to risk of surface water flooding from a one in 50-year rainfall event. This is not within the scope of this study.

Recommendation from NIC report	WRc comment
Interruptions to supply metrics are lagging indicators and are too slow to respond to deterioration and don't incentivise long-term investment in resilience	The incentivisation of investment is not intrinsically linked to the indicators being lagging, but a slow to respond metric can result in investment being delayed if there is insufficient forward planning.
There should be assessment about customers willingness to pay for greater supply resilience rather than a greater probability of relying on alternative supply.	Out of scope of this project. The concept is discussed briefly in section 1.6.
There were missed opportunities to increase supply resilience during the investment programme to develop new water resource schemes in PR24.	Out of scope of this project and not relevant to DWI's remit.
Implementation of a standard should be phased so that it can be delivered alongside the required investment.	Out of scope of this project.
Standards relating to ensuring supply at peak demand should be compatible with plans to reduce per capita consumption.	Agreed. Customer demand is discussed briefly in section 10.
There should be consideration for offering a less resilient supply to business customers at a lower tariff.	While tariffs are out of scope of this project, this links to the concept of willingness to pay and what level of resilience different customer groups want/expect. The NIC themselves note that "*setting standards will ultimately be a political decision but it should be informed by centrally coordinated investigation of consumer preferences using a range of methodologies as different methods can yield very different results*"
The metric for measuring supply at peak demand would need to consider differing levels of peak demand for areas with houses with gardens compared to areas with flats.	Agree that a metric that scales only with number of customers/properties would not be suitable, but there are many aspects affecting demand other than the presence of gardens. A good metric would not be affected by these differences.
A balance should be struck between action to meet peak demand and avoiding causing new problems. Too much water in the supply system so that supply reservoir turnover decreases too much could lead to stagnation threatening drinking water quality.	Agreed. There should also be caution in demanding a level of resilience that is inefficient to provide (e.g. requiring oversized assets) which results in unnecessarily high costs and carbon emissions.

Recommendation from NIC report	WRc comment
Any redundancy standard should consider the system as a whole, from water source to treated water discharged from taps at sub Water Resource Zone level.	Agreed. This is in agreement with our approach to this project.
The department should consider setting limits on the level of resilience expected. In some areas, such as isolated hamlets, it may not be practical or affordable to develop more than one source of supply. This could be addressed by setting a population cap, by saying for example that no group of more than a set number of houses should be supplied by a single source of supply. The exact cap will need to be determined by cost modelling and discussion between regulators and water companies. Alternatively, companies could undertake risk modelling to understand the probability and consequences of failure from single sources of supply.	A risk-based approach is more equitable than a population threshold. However, we agree with the sentiment of this recommendation that practicality, affordability and value for money should be considered.
Infrastructure operators should also consider single sources of failure caused by system interdependencies when planning to address single sources of supply – such as two sources of supply which rely on the same electricity substation	Agreed. Simple requirements on redundancy are likely to be inefficient and not have the intended impact. A one-size-fits-all metric relating to redundancy/reliability is hard to derive and risks stifling innovation and removing common sense/best practice from decision making. We therefore recommend a top-down metric which allows flexibility in how water companies assess resilience and address challenges. The NIC themselves warn against "*incentivising specific behaviours – such as building additional unnecessary redundancy into systems – when other forms of resilience such as enhanced reliability and robustness of existing assets may be more efficient.*"
There does not appear to be a comprehensive and consistent understanding of asset condition across the sector and how this may change in future. A more complete view of asset health in the sector would support a multi-asset management period view of the investment required to maintain asset health and,	While we do not disagree with the benefits to asset management and investment planning of understanding asset health, understanding asset serviceability is more relevant to maintaining a resilient and sufficient water supply.

Recommendation from NIC report	WRc comment
consequently, service performance and reliability.	
Recommendations relating to sewer flooding	Out of scope of this report.
Any metric should be common across all companies.	Agreed. This is consistent with the approach taken in this report.
Companies should not be doubly rewarded, e.g. by ODI payments for reduced mains bursts.	The overlap of performance commitments and existing metrics was considered when developing our recommendations, but ODI payments are out of scope of this report.
With a changing climate, decisions will have to be taken about what constitutes 'new normal' weather under which systems are expected to function as normal, and what is a climate extreme where it is allowable to limit service provision. This will include updating return periods as the climate changes.	Agreed. This report has taken the approach that systems should be designed for the known/foreseeable future based on best available information.

Appendix B Research Protocol

This document sets out the proposed approach that WRc will take for Task 2 (Conduct Search for Evidence & Initial Screening) of DWI project RDE765 (Sufficiency and Resilience of Public Water Supply).

The below forms the Research Protocol for the Quick Scoping Review (QSR) to be undertaken.

B1 Primary Question

The QSR will answer the following Primary Question:

What can the UK learn from how the resilience and sufficiency of water supply, from source to tap, is defined, measured and governed internationally?

To focus the search, the screening, assessment, and review of sources will consider how each of the sources also relates to the following secondary questions.

B2 Secondary questions and subtopics

Defining a resilient and sufficient supply

- What is an acceptable duration of a supply outage?
- What is an acceptable notice period for a supply outage?
- What pressure, flow rate, and volume per day is sufficient? How is this defined for households and other non-household property types, including industry which depends on public potable supply?
- What available system capacity and operation above minimum standards is considered resilient?
- How is risk considered/quantified when assessing acceptable resilience?
- What do customers (household and non-household) expect in terms of resilience and continuity of supply?
- What interruptions / issues are classed as within the water company's control to prevent?
- What are the principles of a resilient water network? How should resilience be defined?

What requirements, standards, targets, and enforcement are in place internationally?

- What are requirements for resilience and redundancy at water treatment works, distribution networks, pumping stations?
- What technical standards are used to define resilient networks? E.g. size of assets, volume retained, system duplication, materials.
- What metrics are used to measure resilience, sufficiency, and continuity of supply throughout the network?
- What key performance indicators (KPIs) do water companies have to report? Do they look at risk or historic performance?
- What standards do water companies have to adhere to?
- What enforcement action is / can be taken when standards are failed?
- Is there evidence that having a resilience / sufficiency standard improves performance?
- What is allowed in terms of water rationing / restrictions / restoration of supply with respect to maintaining a resilience and sufficient supply? What penalties are associated with imposing such restrictions?
- What requirements exist regarding multiple sources, multiple feeds, linked supplies, or redundancy and resilience elsewhere in the system? Are there standards relating to single points of failure?
- What is the hierarchy of resilience measures? What measures are considered most important and effective?
- How are the 4Rs of resilience managed, incentivised and enforced?

B3 Tertiary Questions

When reviewing sources, information will also be gathered to answer the following tertiary questions. It should be noted that **keywords and search strings have not been developed with the purpose of capturing all literature relating to these sub-topics**.

- How is resilience and security defined, monitored, regulated, and enforced **in environmental waters**?

- What headroom in water resources is considered suitably resilient?
- How are future and emerging **external** risks considered and incorporated?
- How is the requirement for sufficiency of supply **balanced** with the need to maintain environmental flows and a changing water environment?
- Do countries enforce standards of service on **customers**, e.g. fixing their own leaks or requiring water companies to do it on their behalf?
- How do other countries deal with any requirements similar to the UK to require supply of water **beyond the boundary** of water company asset ownership?
- Resilience and sufficiency of **non-potable water** supplies.
- Security of supply to critical infrastructure and emergency planning.
- Definitions, measurement, and measures used for security of water supply in other sectors, e.g. aerospace, energy.
- Drought/flood planning and prediction.

B4 Topics out of scope

The following will be **excluded** from this review

- Water supplies which, in England and Wales, would be classed as **private** water supplies.
- Countries or jurisdictions where customers do **not** receive a continuous treated water supply.
- Water supply within a premises (internal plumbing) after the compliance point.
- The sufficiency and resilience of water **sources**.
- Demand management and water efficiency measures.
- Resilience provided through on-site storage, private abstraction, rainwater harvesting, local re-use, or other forms of water supply to premises not provided by the water company.

B5 Geographical reference

All countries or jurisdictions within those countries where customers receive a near continuous supply of treated water from a third party.

B6 Language

The review shall be presented in English but shall endeavour to include sources in all languages relevant to the geographical frame of reference.

B7 Date

No specific timeframe has been set for guidance, policy, regulation, legislation, or associated literature. All current (in use) documents shall be considered in scope.

For academic and industry publications, the earliest publication date of 2000 shall be permitted.

Resilience should be defined over an appropriate time horizon, consistent with the aims and objectives of the NIC’s recommendations. This is unlikely to be significantly less than 25 years or significantly more than 50 years.

Information sources

- Water industry regulators at national, state, and regional levels and other relevant publications, e.g. by water companies or government agencies,
- WHO, including RegNet,
- UN-Water,
- Waterwise Database,
- OECD,
- Geneva Water Hub,
- IWA,
- WAREG (European Water Regulators),

- Academic search engines, including, as a minimum, BASE[19], with possible extension to include results from semantic scholar[20] and/or CORE[21].

B8 Search methodology

B8.1 Country-by-country search

An initial search will be undertaken of water sector bodies and organisations to create a longlist of water regulators and governing bodies who are in geographical scope of the review. Sources such as the OECD's report on the governance of water regulators, publications by the World Bank, WAREG, and members of the IWA Regulator's Forum shall be used.

Internet search engines will then be used to find websites, industry publications, and industry reports that provide evidence to answer the primary question. This might include, for example, annual performance reports/submissions, periodic/regulatory reviews, sector summaries, industry metrics, and legislation/guidance/policy.

B8.2 Academic and grey-literature search

Concurrently, academic search engines and internet searches will be used to search for other evidence. This might include:

- Academic reviews,
- Academic papers,
- Theses and dissertations,
- Industry reports,
- Industry presentations, conference proceedings, or conference papers.

To perform this, search strings will be created based on the following keywords. Search logic will be used whenever possible to combine keywords and search strings to minimise

[19] https://www.base-search.net/Search/Advanced

[20] https://www.semanticscholar.org/

[21] https://core.ac.uk/

overlapping findings. Search strings will be tested and refined to ensure a comprehensive but targeted set of search results is achieved.

- Preservation / security / resilience / sufficiency / reliability / stability / risk [of supply]
- [enforcement / regulation of] security, resilience, sufficiency, reliability, stability
- Adaptability / redundancy / resilience / reinforcement / backup / headroom [of assets]
- Robustness / Rapidity / Resourcefulness / Redundancy / Response / Recovery / Resistance / Reliability
- Recovery capacity, downtime,
- Ample / adequate / sufficient [supply / water / delivery]
- Interruptions to supply / water supply interruptions / continuous supply / continuity of supply / loss of supply / outage
- Water rationing / water restrictions / use restrictions / continuity of supply

B8.3 Gathering documents which outline the UK framework

Discussion with WRc experts and review of the below known sources will identify any secondary legislation, underlying guidance, or other relevant material which would help to explain the current UK standards for, performance of, measurement of, and legislative powers for resilience and sufficiency of supply in England and Wales. This will include Ofwat's Towards Resilience paper and water company and industry publications. In addition, in combination with work strand B8.1), this shall be extended to cover Scotland, Northern Ireland, the Republic of Ireland, and other members of the British Isles.

Appendix C Definitions of resilience

Table C.1 International definitions of resilience

Term	Metric	Source
Water supply security	Average per capita water availability	Within review by Krueger (Krueger, et al., 2019)
Water supply security	Proportion of population living in water poverty	Within review by Krueger (Krueger, et al., 2019)
Robustness	The strength of the system to withstand pressure: the maximum duration in which the system is capable of maintaining its highest potential supply level under pressure	(Amarasinghe, 2014)
Hydraulic reliability	The performance of the system to satisfy the required water demand.	(Naguib, et al., 2019)
Component reliability	The probability that a component has no failure during its lifetime.	(Naguib, et al., 2019)
Mechanical reliability	measures the effect of component failure on the system performance, mechanical reliability depends on both hydraulic reliability and component reliability.	(Naguib, et al., 2019)
Network/System reliability	The minimum mechanical reliability of all system components.	(Naguib, et al., 2019)
System reliability	Marginal capability to meet users' needs	(Nair & Neelakantan, 2022)
System reliability	The capacity of a water distribution network to fulfil requirements with significant pressure under normal and abnormal situations.	(Nair & Neelakantan, 2022)
Reliability	The degree to which the system minimises level of service failure frequency over its design life when subject to standard loading.	(Butler, et al., 2014)
Reliability	Reliability addresses performance within the design life of the system and during periods in which the required level of service is expected to be met (i.e., when subject to standard loading/in the absence of exceptional conditions). Reliability-based design aims to provide fail-safe performance, that is, avoid failure.	(Butler, et al., 2016)
Reliability	How often a system fails.	(Hashimoto, et al., 1982)

Term	Metric	Source
Reliable	Of the eight provided definitions, many of them focused on the ability and/or probability of successful water delivery. This was expressed in terms of either the performance of a particular system component or the failure frequency. Four explicitly referred to reliability in terms of meeting water. "*matching the state's demands for reasonable and beneficial use of water to the available supply.", "a measure of the quality and quantity of services proved to meet a community's needs and expectations.*" The degree to which the system minimises the level of service failure frequency over its design life when subject to standard loading. The probability that a water supply network will satisfy the design demand.	(Hopkins & Sowby, 2023)
Hydraulic dependability	Is a system's capacity to provide needed water needs and force under normal and pathological conditions.	(Nair & Neelakantan, 2022)
Mechanical dependability	System architecture measuring system connectivity under specified failure scenarios.	(Nair & Neelakantan, 2022)
Sustainability	The degree to which the system maintains levels of service in the long-term whilst maximising social, economic and environmental goals.	(Butler, et al., 2016)
Sustainability	Sustainability relates to the level of service provision (performance) and social, economic, and environmental consequences in the long term (i.e., up to and beyond design life).	(Butler, et al., 2016)
Resilience	The degree to which the system minimises level of service failure magnitude and duration over its design life when subject to exceptional conditions.	(Butler, et al., 2014)
Resilience	Performance during the design life but addresses performance during periods in which the required level of service is not met (i.e., when subject to threats). Resilience-based design aims to overcome failure and ensure that the system is safe to fail.	(Butler, et al., 2016)
Resilience	The "*ability to reduce the magnitude and/or duration of disruptive events*" as determined by the "*ability to*	(National Infrastructure Advisory Council, 2016)

Term	Metric	Source
	anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event".	
Resilience	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.	Presidential Policy Directive (PPD) 21: Critical Infrastructure Security and Resilience (America's Cyber Defense Agency, 2013)
Resilience	The ability of the system to provide a reliable level of service despite external shocks, and to quickly rebound to the desired service levels after said shocks.	World Bank (Stip, et al., 2019)
Resilience	The capacity to adapt to unexpected threats once they have materialized and learn to recover fully	Within review by (Nair & Neelakantan, 2022)
Resilience	Adapting present resources and skills to shifting scenarios and operating environments.	Within review by (Nair & Neelakantan, 2022)
Resilience	The ability of a community water system or an asset of a community water system to adapt to or withstand the effects of a malevolent act or natural hazard without interruption to the asset's or system's function, or if the function is interrupted, to rapidly return to a normal operating condition	(congress.gov, 2018)
Resilience	The ability of an asset or system to withstand an attack or natural hazard without interruption of performing the asset or system's function or, if the function is interrupted, to restore the function rapidly	(ANSI/AWWA, 2010)
Water UK	the ability of assets, networks and systems to anticipate absorb, adapt to and / or rapidly recover from a disruptive event to customers	(Water UK, 2015)
Engineering resilience	46% of papers used an engineering resilience definition The time it takes for a system (typically built infrastructure) to return to normal, or maintain reliability and functionality, after a disturbance	(Rodina, 2018)

Term	Metric	Source
Engineering resilience	a system's speed of return to equilibrium following a shock, indicating that a system can only have a single stability regime	Quinlan 2016 citing Pumm 1984
Socio-ecological resilience	The capacity of coupled social-ecological systems to cope or transform in the face of change (19% of papers)	(Rodina, 2018)
Ecological resilience	The capacity of a system (typically an ecological system) to absorb a shock without changing states (11% of papers)	(Rodina, 2018)
Community resilience	The ability of communities to cope or adapt in the face of change (8% of papers)	(Rodina, 2018)
Institutional resilience	The ability of institutions of government to cope or adapt in the face of change (7% of papers)	(Rodina, 2018)
Unspecified resilience	12% of papers talk about resilience without defining it	(Rodina, 2018)
Characteristics of a resilient system (design)	Robust (30%) Redundancy (14%) Ability to recover quickly (6%) Buffer capacity (3%) Muli-functional systems (1%)	(Rodina, 2018)
Characteristics of a resilient system (properties)	Adaptive (36%) Interconnected (33%) Flexible (30%) Diversity (13%) Transformative (12%)	(Rodina, 2018)
Resilience	How quickly a system returns to a satisfactory state once a failure has occurred	(Hashimoto, et al., 1982)
Vulnerability	How significant the likely consequences of a failure may be	(Hashimoto, et al., 1982)
Resilience	Resilient systems withstand, respond to, and adapt more readily to shocks and stresses to bounce back stronger after tough times, and live better in good times.	(Rockefeller Foundation, 2015)

Appendix D Resilience frameworks

D1 'How tough is WASH' framework

The How tough is WASH framework is a tool designed to assess the climate resilience of water, sanitation and hygiene services, but is particularly focussed on low and middle-income countries in rural and small-town contexts (Howard, et al., 2021). However, the Pacific Institute claim it "*may therefore be relevant to and practical for resource and capacity-constrained frontline communities in the US*". There are six domains of resilience in the framework:

- Infrastructure: Water yield, system integrity and level of suitability of infrastructure.
- Environment: climatic, environmental and societal hazards.
- Management: management structures, understanding, and social representation.
- Institutional support: support for climate adaptation, emergency response, inter-sector coordination and risk management.
- Supply chains: availability or spares and consumables and robustness of the supply chain and supporting infrastructure.
- Community governance and engagement: engagement/participation, inclusivity and reporting mechanisms.
- There is a Likert scale for each domain ranging from 1 (very low resilience) to 5 (very high resilience). The scores reflect the likelihood that the water supply or sanitation system could cope with climatic events and prevent adverse impacts.

Assessment: Other frameworks are more specific and relevant to the UK context.

D2 EPA's Vulnerability Self-Assessment Tool

The US EPA's Vulnerability Self-Assessment Tool (VSAT) can be used to assess risk and resilience of water company assets. It has designed to be applicable for all sizes of water utility to help identify the highest risks to critical operations and to identify cost-effective measures to reduce those risks. Certification is provided upon completion of the tool (EPA, n.d.).

Assessment: This tool could be used as a template for the UK to guide water companies through assessment of risks, critical assets and countermeasures. However, in its current form it is applicable only to the US context.

D3 EPA Effective Utility Management

The US EPA's guidance on effective utility management includes a self-assessment where utilities can score their current level of achievement from 'effective, systematic approach and implementation, consistently achieve goals' to 'no system for addressing this'. They can also score attributes according to their importance to the business allowing them to prioritise. The following attributes are scored:

- Community sustainability
- Customer experience and satisfaction
- Enterprise resiliency
- Financial viability
- Infrastructure strategy and performance
- Operational optimisation
- Regulatory and reliability performance
- Stakeholder understanding and support
- Water resource sustainability
- Workforce development

Assessment: This is a good high-level framework for assessing basic overall business resilience is too detached from the end experience received by customers and is not sufficiently detailed or prescriptive to be a useful assurance tool or regulatory framework.

D3.1 EPA Climate Resilience Evaluation and Awareness Tool

The US EPA's Climate Resilience Evaluation and Awareness Tool (CREAT) was developed to assist water utilities assess and manage climate-related risks to infrastructure and operations. It is aimed at managers and operators. The 5 modules (climate awareness, scenario development, consequences and assets, adaptation planning and risk assessment) result in a risk assessment which allows users to compare risks and evaluate the effectiveness of different adaptation options to inform decision-making. CREAT can import results from VSAT. (EPA, n.d.)

CREAT covers the following shocks and hazards:

- Water Supply Management: drought, seasonal demand, snowpack, reservoir storage, and low streamflow conditions;
- Peak Service Challenges: stormwater runoff, seasonal demand, and discharge under low receiving water flow conditions;
- Water Quality Management: runoff, treatment, violations, saltwater intrusion, source water turbidity, and algal blooms;
- Natural Disasters: fires, floods, tornadoes, and ice storms;
- Ecosystem/Landscape Management: coastal erosion, wetland loss, and endangered species protection;
- Population/Demographic Changes: customer base, land use, and workforce availability;
- Sector Water/Service Needs: agriculture, energy sector, health services, and local industries;
- Interdependent Sector Reliability: power sector, transportation, and chemical suppliers;
- Sea Level Rise (SLR): saltwater intrusion, and coastal storm surges

Assessment: This framework shows potential for UK deployment. However, this would require data gathering (particularly on the costs and benefits and quantification of risk impacts).

D3.2 Safe & SuRe framework

The Safe & SuRe framework was developed by the University of Exeter Centre for Water Systems. It aims to identify opportunities to increase the resilience of water system design by considering the relationship between threats[22] and their consequences.

It defines a Safe system as one which is resistant and stable which provides the required level of service during high probability (normal) situations. A reliable system should be assessed on how well it prevents failures during its design life.

[22] "*any event with the potential to reduce the degree to which the system delivers a defined level of service*"

A SuRe system is one that is Sustainable and Resilient. A resilient system is defined as one which is flexible, connected, and has redundancy. Resilience is appliable when the system is working outside of its committed level of service in extreme, low probability situations. A resilience systems should be assessed on how well it minimises the duration and magnitude of failures.

A sustainable system is one that is equitable, affordable and low impact. A sustainable system should be measured according to how well it maximises social, economic and environmental capital.

Assessment: This provides useful and clear definitions of what makes a system resilient.

D3.3 UKWIR framework for resilience performance measures

UKWIR's report on resilience performance measures identifies ENISA guidance (European Union Agency for Network and Information Security (no longer available), now the European Union Agency for Cybersecurity) as the most comprehensive guidance on 'good practice' for measuring resilience. The UKWIR report summarises the "*good practice principles for resilience metrics*" based on this framework:

- Business characteristics
- Readily obtainable (complexity should not outweigh advantages)
- Relevant (should provide useful information for tracking performance, allocating resources and directing strategy towards business objective)
- Technical characteristics
- Quantifiable (should define the quantity and unit of measurement and uncertainty understood)
- Repeatable (reproducible yielding consistent results if the correct method is followed with assumptions understood)
- Comparable (any two measured values should be able to be compared)

It also gives mention to the UK Civil Protection Terminology (LUCPT) under the Civil Contingencies Act 2004, which identifies and establishes a clear set of roles and responsibilities for those involved in emergency preparation and response at the local level, and the Highways Agency's 'Well managed highway infrastructure – a code of practice' (2016) which was used in the previous 2006 UKWIR guidance 'Resilience, making a case for PR14'.

Measuring service disruption should either describe the consequences or act as a proxy for the risk of ‘unacceptable’ disruption occurring.

Assessment: We agree that this represents good practice for the definition of resilience indicators.

D3.4 UK Government Resilience Framework

The UK government’s resilience framework sets out a strategic approach to anticipating, preventing, withstanding, responding to and recovering from both acute and chronic risks, including climate change, health emergencies and flooding. (HM Government, 2022) The framework is built on the principles of a shared understanding of risk, investment to prevent risks materialising and preparing for those that cannot be avoided, and taking a whole-of-society approach, working cross-sector to develop resilience. Included within the framework is the National Security Risk Assessment method and the roles of local resilience forums. The framework designates water as one of the UK’s 13 critical national infrastructure sectors and also calls for operators of essential services such as water to identify, communicate with and support vulnerable customers during outages.

Assessment: The recommendations under this framework to communicate and collaborate cross-sector and with local groups should not be forgotten, but this is detached from end-user experience so may be inappropriate as the basis for DWI metrics and standards.

D3.5 Keeping the Country Running

“*Keeping the Country Running*” is an advisory guidance document produced by the UK Cabinet Office in 2011 to support infrastructure owners and operators, emergency responders, industry groups, regulators, and government departments. Its aim is to help these stakeholders work together to improve the resilience of critical infrastructure and essential services, such as water, energy, transport, and communications, against natural hazards like flooding, severe weather, and other environmental risks. It sets the requirement that critical sectors such as water develop and regulatory update their resilience plans and calls on regulators to ensure that investment is proportionate to risk and that resilience is considered.

Keeping the Country Running proposed the widely adopted ‘4Rs’ resilience framework (Box 1) and a resilience of definition which Ofwat’s Task and Finish Group asserted “*is now considered to be the industry accepted definition*”.

Box 1: 4Rs of Infrastructure Resilience (Cabinet Office, 2011)
2.12 The Resistance element of resilience is focused on providing protection. The objective is to prevent damage or disruption by providing the strength or protection to resist the hazard or its primary impact. Resistance strategies have significant weaknesses as protection is

often developed against the kind of events that have been previously experienced, or those predicted to occur based on historic records. Protective security measures aimed at reducing the impact of malicious threats may or may not help to reduce the impact of natural hazards. Disruptive events can exceed the standards provided for protection thus resulting in loss or damage and significant impacts, particularly where the resistance strategy is the only component of a resilience strategy.

2.13 The Reliability component is concerned with ensuring that the infrastructure components are inherently designed to operate under a range of conditions and hence mitigate damage or loss from an event. The tendency of a reliability strategy is to focus only on the events within the specified range, and not events that exceed the range. This can lead to insufficient awareness or preparation for events outside of the range, and hence significant wider and prolonged impacts can occur. Reliability cannot therefore be guaranteed, but deterioration can sometimes be managed at a tolerable level until full services can be restored after the event.

2.14 The Redundancy element is concerned with the design and capacity of the network or system. The availability of backup installations or spare capacity will enable operations to be switched or diverted to alternative parts of the network in the event of disruptions to ensure continuity of services. In some of the sectors of national infrastructure, redundancy strategies would lead to an initial loss of performance until the alternative infrastructure can be brought into operation. The telecommunications sector employs a redundancy strategy to provide the capacity and flexibility to meet peak demand for services and enable re-routing of communications „traffic" in the event of failure or loss of components. In this sector, the switch over to maintain services is instantaneous. The resilience of networks reduces when running at or near capacity, although in some sectors or organisations it is recognised that it may not always be feasible to operate with significant spare capacity within the network.

2.15 The Response and Recovery element aims to enable a fast and effective response to and recovery from disruptive events. The effectiveness of this element is determined by the thoroughness of efforts to plan, prepare and exercise in advance of events. The strategy may differentiate between the response and the recovery. Some owners of critical infrastructure understand the weaknesses in their networks and systems and have arrangements in place to respond quickly to restore services. Recovery is considered in pre-event planning to explore opportunities to reduce future risks and/or build resilience in infrastructure during the recovery stage.

2.16 Hence resilience of infrastructure is provided through (a) good design of the network and systems to ensure it has the necessary resistance, reliability and redundancy (spare capacity), and (b) by establishing good organisational resilience to provide the ability, capacity and capability to respond and recover from disruptive events. The latter is gained through business operations and appropriate support for business continuity management.

(Butler, et al., 2016) criticised this guidance for mixing properties of resilience with resilient performance saying their "*advice to improve resilience by increasing resistance, reliability, redundancy, and response and recovery – an unspecified mix of performance measures (reliability and response and recovery [time]) and properties (resistance and redundancy)*".

Assessment: The existing guidance to create and update resilience plans and monitor investment spend could be used as the basis for assurance of resilience. The '4Rs' framework has the advantage of being well known and commonly adopted in the UK but should be compared with others such as the Safe & SuRe framework.

D3.6 Water safety planning

The water safety planning process is a risk-based approach designed to ensure consistent delivery of safe drinking water from source to tap. It is based upon the WHO's water safety planning framework but is adapted for the UK in BS 8680:2020 Water quality. Water Safety Plans. Code of practice., which adapts these principles to UK-specific legislation and operational contexts. Water safety plans must consider, assess and prioritise hazards to all stages of the water network, including those that will affect the quantity of water treated and distributed.

The IWA is also working on a project "*Climate Resilient Water Safety Planning to Improve Water Supply and Public Health*". The project is addressing how utilities through WSP can better prepare and respond to extreme weather events; as well as undertaking strategic awareness approaches to involve key ministries in supporting the institutionalisation of WSP within other countries (IWA, 2019).

Assessment: As an existing planning activity that requires water companies to assess and quantify risks to their system and consider mitigation, water safety planning may offer low effort / efficient means of providing quantification, benchmarking and regulatory assurance of water supply resilience and sufficiency. Benefits include the segmentation of the water system (which we have chosen to adopt in this report), but limitations include the lack of consistent approach to water safety planning and reporting, infrequency of updates, consideration of current as opposed to future risks, and a potential bias towards risks to water quality as opposed to quantity.

D3.7 Utility Resilience Index

The Utility Resilience Index is a tool designed to assess and benchmark the resilience of water and wastewater utilities, producing a score out of 100. (Morley, 2012) It scores the following on a 1-5 scale:

- Emergency response plan (from 'No emergency response plan' to 'Functional exercises on the emergency response plan conducted')

- Operational

- National incident management system compliance - a framework for incident response and management including roles & responsibility (from ‘No incident command system / national incident management system training provided’ to ‘Utility certified as national incident management system compliance’)

- Mutual aid and assistance (from ‘None’ to ‘Interstate and intrastate agreement’)

- Emergency power for critical operations (from ‘None’ to ‘Greater than 72 hours of backup power’)

- Minimum daily demand– ability to meet minimum daily demand when production is nonfunctional (from ‘None’ to ‘Greater than 72 hours’)

- Critical parts and equipment – lead time for repairs replacement or recovery (from ‘3-4 weeks or greater’ to ‘Less than 24 hours’)

- Critical staff resilience – percentage of response-capable staff available for critical operations and maintenance positions (from ‘Less than 10%’ to ’75-100%’)

- Business continuity plan (BCP) – as recommended in ANSI/AWWA G430-09 and ANSI/AWWA G440-11 (from ‘No BCP’ to ‘Annual commitment of resources and BCP exercised’)

Assessment: Financial resilience has not been considered within the scope of this project as it is detached from customer experience. However, this composite index includes a number of relevant and non-overlapping metrics and provides a good framework for benchmarking resilience.

D3.8 Resilience Practical Framework (RPF) for Water Infrastructure

The resilience practical framework is intended to help companies complete a self-assessment of the maturity of a utility’s current level of resilience, identify gaps, think about strategies to improve and provide guidance of where to go to get helpful information to assist with the implementation of the required changes.

Relating to clean water, companies score themselves from 0 (below compliance) to 5 (advanced) for chosen resilience outcomes. The following are suggested:

- Resource adequacy (water)

- Product quality
- Service reliability
- Operational improvement
- Emergency response and recovery preparedness
- Customer satisfaction
- Stakeholder understanding and support
- Employee and leadership development
- Environmental protection/enhancement
- Infrastructure stability
- Financial viability.

The framework would then see them identify gaps compared to the desired maturity level and choose strategies to address the gaps. (Water Research Foundation, 2023)

Assessment: The framework is intended to provide a common structure but allow companies to tailor the resilience definition and resilience outcomes to their specific context. It is focussed on driving improvement, so could be used to demonstrate progress. However, while freedom with determining how to ensure resilience is likely to be beneficial, it is likely that a common set of resilience outcomes and a common definition of resilience would be most beneficial for the DWI's context. As such, this is likely to be more suitable as an internal tool rather than a regulatory framework.

D3.9 Yorkshire Water's resilience framework

Yorkshire Water have a resilience framework which is used operationally and for investment decision making. It applies the '4R's' approach through an 'identify and understand risk', 'mitigate' and 'monitor' using the maturity assessment scale in BS 65000. They defined 16 resilience systems across corporate, financial and operational resilience, each of which is assessed against a set of shocks and stresses. Interdependencies are mapped and business units identify their most significant shocks and stresses (Yorkshire Water, 2018) (Yorkshire Water, 2019).

The resilience frameworks created by water companies show significant inconsistency in what shocks and stresses they consider. Anglian Water, Yorkshire Water and Southern Water explicitly listed these and they are summarised in Table G.1 (Appendix G).

Figure 12.1 Yorkshire water's integrated resilience framework

Assessment: This framework appears transferable. However, an agreed list of shocks and stresses would be required.

D3.10 Wessex Water

Wessex Water's framework sees then identify risks including acute shocks (e.g., floods, cyber-attacks) and chronic stresses (e.g., climate change, skills shortages). (Wessex Water, 2023) Risks are assessed qualitatively and quantitatively, using probability-impact scales and scenario analysis. Drinking Water Safety Plans (DWSP) and Wastewater Asset Risk Management (WARMs) systems inform risk assessments. Options to address risks are identified and screened using the Tolerate, Operate, Collaborate, Optimise, Build smarter hierarchy. Interventions are evaluated against the 5Rs of resilience (Re-evaluate, Resistance, Reliability, Redundancy, Response and Recovery).

Assessment: This framework appears robust, but an element of prioritisation or quantification may be required to make it feasible in practice for all risks facing the business.

D3.11 Anglian Water

Anglian Water developed a framework *"to apply 'Resilience in the Round' thinking at a practical level*". A maturity assessment was used to score current objectives and common practices against Anglian Water's current initiatives and planned future investment.

Assessment: The maturity self-assessment approach could be applied industry-wide, but the specific Anglian Water implementation is not a suitable framework.

D3.12 Dŵr Cymru Welsh Water Resilience Wheel

Developed by Arup (who also created Anglian Water's framework), the wheel lists and groups operational resilience factors, considering the resilience of people, infrastructure and environment, and finance and governance. They also produced in response to Ofwat's resilience challenge a set of performance commitments linked to resilience investment and mechanisms for monitoring risks (Dŵr Cymru Welsh Water, 2018) (Dŵr Cymru Welsh Water, 2019)

Theme	First Outer Ring Focus Areas	Indicators/Activities
People	Engagement & Partnership with Customers	Customer education, Community support, Vulnerable customer services
	Employee Wellbeing & Skills	Training & development, Staff wellbeing programmes, Diversity & inclusion
	Protecting Public Health	Water quality monitoring, Emergency planning, Public health partnerships
Infrastructure & Environment	Robust & Adaptable Physical Assets	Asset maintenance, Investment in new infrastructure, Network resilience projects
	Efficient Resource Use	Leakage reduction, Water efficiency, Energy efficiency, Waste minimisation
	Working with the Natural Environment	Catchment management, Biodiversity projects, Climate change adaptation
Finance & Governance	Financial Sustainability & Flexibility	Long-term financial planning, Efficient investment, Affordability initiatives
	Strong Governance & Leadership	Board oversight, Transparent reporting, Ethical standards
	Risk Management & Compliance	Risk assessment, Regulatory compliance, Business continuity planning

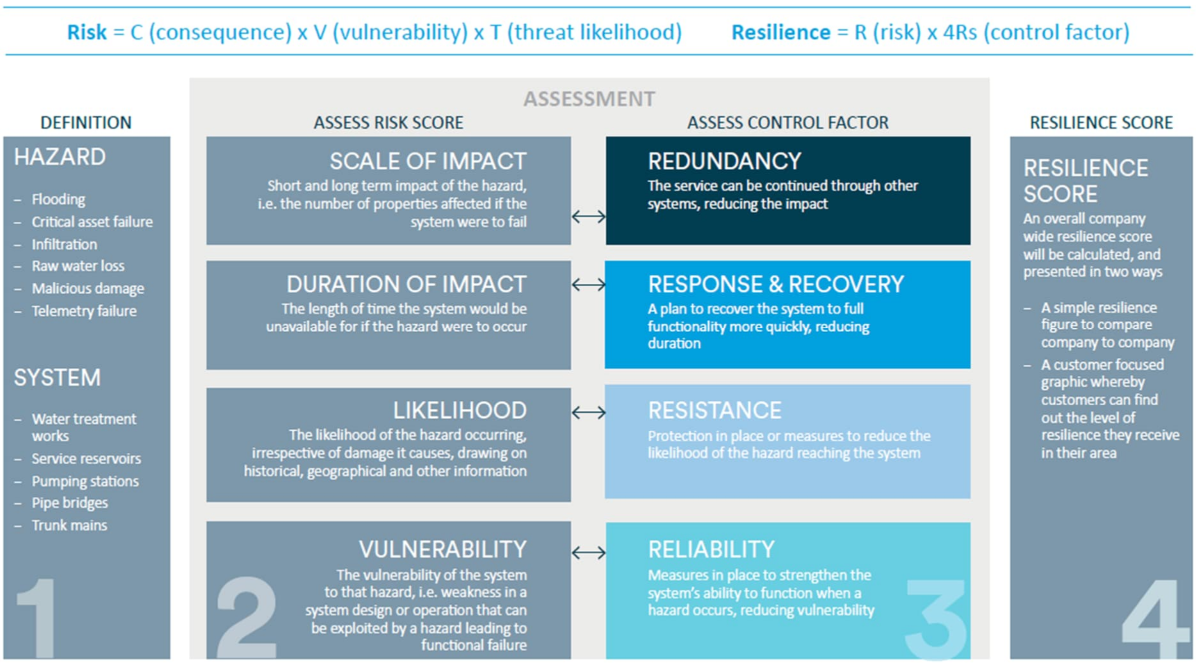
Assessment: The wheel lacks practical use for DWI's purposes.

D3.13 UU resilience metric

United Utilities (United Utilities, 2017) has published a proposed ‘resilience metric’ for the sector, which they describe as “*a measure to indicate the population served by satisfactorily resilient services, by employing a risk based resilience assessment.*” Their approach is based on characterising hazards that threaten the system and then adjusting the risk measure based on the ‘control factors’ in place, which are determined by the ‘4Rs’ of infrastructure resilience.

Their metric has initially been applied to water supply from water treatment works but “*could, however, equally be adapted to cover other single points of failure such as aqueducts, trunk mains, potable water storage and pumping stations*”. The measure calculates the population served by “satisfactorily resilient services” (Figure 12.2)

Figure 12.2 Schematic illustrating UU’s resilience metric



Assessment: Assessing risk (consequence and probability) and adjusting for control factors reflects best practice.

D3.14 Water Resilience Assessment Framework

CEO Water Mandate developed the Water Resilience Assessment Framework (WRAF), in collaboration with the Pacific Institute, the Alliance for Global Water Adaptation, the International Water Management Institute, and World Resources Institute. It aims to create common measurable goals and outcomes for stakeholder and resilience planning. The WRAF consists of four key steps: visualising the system, developing a resilience strategy, testing the resilience strategy, and evaluating. Three guidance documents support the framework alongside a quantitative scoring tool which assesses resilience against a number of quantitative metrics (Fleming, et al., 2024).

The CEO Water Mandate's 'Water Resilience Assessment Framework Guidance for Water Utilities' provides six resilience characteristics (Chapagain, et al., 2021) to help track, measure and assess the status of the resilience of a water supply network: (Fleming, et al., 2024)

- Robustness: The system is designed to perform at or beyond the levels of high-confidence, low uncertainty risks.
- Redundancy: The system has spare capacity intentionally created to accommodate disruption, extreme pressures or demand surges.
- Flexibility: The system can be altered and adapted in response to potential shocks and stresses or adjusted to take advantage of opportunities.
- Integration: The system components are linked and coordinated while also able to be isolated.
- Inclusiveness: The system has effective mechanisms for broad consultation and engagement of individuals and communities, including the most vulnerable.
- Justice and Equity: The system ensures that all stakeholders within a system are provided with equitable water access, rights and allowances.

Assessment: The Water Resilience Assessment Framework appears to be well regarded and widely adopted. It offers a suitable framework and common language and allows for scoring of resilience for benchmarking and comparison, but its generality could make it challenging to apply.

Appendix E Water Resource metric calculations

E1 SoSI

To calculate SoSI, the supply demand balance (SDB) for each water resource zone (WRZ) must first be calculated using Equation 2.

Equation 2 Supply Demand Balance (SDB) as percentage of dry year DI Equation (Ofwat, 2006)

$$\mathbf{SDB_p} = \frac{\mathbf{WAFU+BI-BE-DI-TH}}{\mathbf{DI}}$$

Where:

- SDB_p is the supply demand balance as a percentage of dry year DI.
- WAFU is water available for use under the Environment Agency definition.
- BI is bulk imports.
- BE is bulk exports.
- DI is dry year distribution input.
- TH is target headroom.

The population within WRZs that have a deficit should then be identified as a percentage of the water company's total population served. Should the SDB be 0 or a positive number, this value is 0.

The Zonal Index (ZI) for each WRZ is calculated using Equation 3, and summed together to identify the company ZI.

Equation 3 Company Zonal Index (Ofwat, 2006)

$$\mathbf{ZI_c} = \sum_i \mathbf{SDB_{pi}}^2 * \mathbf{P_{di}} * \mathbf{100}$$

Where:

- ZI_c is the company zonal index.
- SDB_{pi} is the supply demand balance as a percentage of dry year DI for WRZ i.
- P_{di} is percentage population impacted by deficit for WRZ i.

Finally, the SoSI is calculated with Equation 4 and rounding down to the nearest whole number.

Equation 4 Company-wide SoSI Equation (Ofwat, 2006)

$$\mathbf{SoSI} = (\mathbf{1} - \mathbf{ZI_c}) * \mathbf{100}$$

Where:

- ZI_c is the company zonal index.

E2 SDBI

SDBI is based on the difference between the available headroom and the target headroom specified in a WRMP for each WRZ. The calculation follows the method for SoSI, with previously referred to as SoSI score representing the company-wide SDBI. However, for SDBI the score should be calculated for each WRZ as well. SDBI can be calculated using dry year DI and critical period DI. If this is done the lowest score will be used as the WRZ SDBI number.

E3 Reservoir Vulnerability

Equation 5 Reservoir Vulnerability (Xefide & Ophori, 2009)

$$\eta' = \frac{\sum_{i=1}^{f_s} \max\,(sh_k)}{f_f}$$

Where:

- η' is the vulnerability.
- $\max(sh_k)$ is maximum shortfall during the kth continuous failure sequence.
- f_s is the number of continuous failure sequences in the simulation.

Normally, the vulnerability is expressed in dimensionless units by dividing by the target demand during the failure period. This is denoted by Equation 6.

Equation 6 Dimensionless reservoir vulnerability (Xefide & Ophori, 2009)

$$\eta' = \frac{\sum_{i=1}^{f_s} \max\,(sh_k)}{f_f}$$

Where:

- η is the dimensionless vulnerability.
- η' is the vulnerability.
- D is the target demand during failure.

Appendix F Customer focussed license condition

<u>The following text applies to England. Similar wording applies to Wales.</u>

G1 In this condition:

G1.1 an 'incident' means an event or situation which causes or may cause damage, disruption, distress or inconvenience to the Appointee's customers in their capacity as such which is not trivial.

G2 The Appointee must:

G.2.1 develop or have in place policies and approaches to meet the principles for customer care set out in paragraph G3, consulting with the Consumer Council for Water where appropriate;

G.2.2 implement or continue to follow those policies and approaches in a way that meets the principles for customer care set out in paragraph G3; and

G.2.3 explain in a manner that is effective, accessible and clear how it is meeting the principles set out in paragraph G3

G3 The principles for customer care are:

G3.1 The Appointee is proactive in its communications so that its customers receive the right information at the right time, including during incidents.

G3.2 The Appointee makes it easy for its customers to contact it and provides easy to access contact information.

G3.3 The Appointee provides appropriate support for its customers when things go wrong and helps to put things right.

G3.4 The Appointee learns from its own past experiences, and shares these with relevant stakeholders. The Appointee also learns from relevant stakeholders' experiences and demonstrates continual improvement to prevent foreseeable harm to its customers.

G3.5 The Appointee understands the needs of its customers and provides appropriate support, including appropriate support for customers in vulnerable circumstances, and including during and following incidents.

G3.6 As part of meeting principle G3.5 above, the Appointee provides support for its customers who are struggling to pay, and for customers in debt

Appendix G Shocks and stresses

Table G.1 Mapping of shocks and stresses considered by 3 English water companies in their resilience proposals to Ofwat (Southern Water, 2023) (Arup, 2018) (Yorkshire Water, 2019)

Category	Shocks and stresses	Southern Water	Anglian Water	Yorkshire Water
Climate & Natural Environment	Coastal erosion	✓	✓	✓
Climate & Natural Environment	Contamination	✓	✓	
Climate & Natural Environment	Environmental changes		✓	✓
Climate & Natural Environment	Extreme rainfall			✓
Climate & Natural Environment	Failure to adapt to / mitigate climate change	✓	✓	✓
Climate & Natural Environment	Fire		✓	
Climate & Natural Environment	Flood risk from rivers, surface water and sea	✓		
Climate & Natural Environment	Heat stress	✓		
Climate & Natural Environment	Infectious disease (flora, fauna)		✓	✓
Climate & Natural Environment	Natural geohazards			✓
Climate & Natural Environment	Saline intrusion	✓		
Climate & Natural Environment	Space weather			✓
Climate & Natural Environment	Storms and high winds			✓
Climate & Natural Environment	Subsidence	✓		✓
Climate & Natural Environment	Temperature extremes		✓	✓
Economic & Political	Bad debt		✓	✓
Economic & Political	Economic shocks & economic performance		✓	✓
Economic & Political	Financial crises		✓	
Economic & Political	Industrial disputes		✓	✓
Economic & Political	Inflation		✓	
Economic & Political	Political & macro industry change		✓	✓

Category	Shocks and stresses	Southern Water	Anglian Water	Yorkshire Water
Economic & Political	Resource scarcity		✓	
Economic & Political	Rising cost of debt		✓	
Economic & Political	Severe energy price changes		✓	
Economic & Political	Skilled labour shortage / skills shortage		✓	✓
Economic & Political	State collapse or crisis		✓	
Economic & Political	State provision of services		✓	
Economic & Political	Supply chain failure		✓	
Economic & Political	Unemployment and underemployment		✓	
Geographical	Demographic changes		✓	
Geographical	Land use changes		✓	
Geographical	Population growth	✓		✓
Geographical	Urban creep		✓	✓
Human	Changes in customer behaviour and expectations			✓
Human	Civil unrest		✓	✓
Human	Cyber attacks	✓	✓	✓
Human	Data fraud/theft		✓	
Human	Harassment and discrimination			✓
Human	Hoax calls		✓	
Human	Increasing inequality and income disparity		✓	
Human	Infectious disease (human)		✓	✓
Human	Lifestyle changes		✓	
Human	Malicious damage	✓		
Human	Migration		✓	
Human	Rising chronic and lifestyle diseases		✓	
Human	Telecommunication failure		✓	

Category	Shocks and stresses	Southern Water	Anglian Water	Yorkshire Water
Human	Terrorist attack		✓	✓
Human	Vandalism		✓	✓
Human	Vulnerable communities and customers			✓
Internal	Ageing infrastructure	✓	✓	✓
Internal	Critical asset failure	✓	✓	✓
Internal	Digital revolution & disruptive technology			✓
Internal	Environmental pollution		✓	✓
Internal	False positive alarms		✓	
Internal	Leakage		✓	
Internal	Loss of raw water	✓		
Internal	Structural change	✓	✓	
Regulatory	Abstraction license changes		✓	
Regulatory	Changing regulation, policy and international governance		✓	
Regulatory	Failure of national, regional or global governance		✓	
Regulatory	Legal structures		✓	
Other	Nuclear incidents		✓	
Other	Power interruptions & outages	✓	✓	✓

Appendix H Good practice in incident response

H1 Introduction

While customer engagement and incident response are tertiary to the scope of this project, this section provides a short summary of what is considered by DWI, Ofwat, and the NI Utility Regulator to represent best practice with regard to communication and customer support prior to and during interruptions to supply. (DWI, 2023) (Ofwat, 2024) (Ofwat, 2018) (Utility Regulator, 2011) It is our recommendation that such actions be tied to the concept of sufficiency and resilience of supply, that is, should planned or unplanned interruptions be permitted under future guidance, compliance with such guidance should include standards relating to customer communication and customer support. As such, it should be considered how the following list of best practices can be encouraged, measured, and enforced.

Affinity Water has expressed that the current 1989 regulations, are in need of update. With regard to the requirement that a water undertaker must notify customers of where they can obtain an alternative supply in the event of a supply interruption, they state that this specifically relates to a company "*erecting a standpipe on the nearest 'live' hydrant. A standpipe on a hydrant is no longer deemed acceptable for drinking water quality purposes, and this clause should be removed as it is misleading [if an alternative mains supply cannot be provided]*" (Affinity Water, 2023). Instead, the use of bottled water and, in some cases, tankers are more common.

H2 Measures relating to planned incidents and unplanned incidents which can be foreseen or are likely to occur

- Having winter preparations developed and in place by the end of October, with company communications preparing customers for adverse weather soon afterwards.

- Hold preparatory meetings with local resilience forums in advance expected adverse weather or other impending risks, collaborating with local authorities to ensure plans were in place in case of problems, including refreshing arrangements for the location of bottled water stations.

- Respond to unplanned issued by considering changes to non-urgent planned works to minimise disruption and increase the number of staff across multiple business areas, such as phone contact centres and engineers to respond to customer problems.

- Share data with relevant local so that there is a coordinated and customer-centric approach.

- Incident teams should be set up as early as possible, and prior to customers losing supply.

- Take steps to minimise disruption though proactive network management prior to, and during events, for example, repairing leaks, utilising storage capacity and using remotely operated pressure values to throttle demand.

- Proactively provide alternative supply to vulnerable customers before supply is lost.

- Historical events should be used to benchmark resilience in the run-up to likely incidents and to inform the response plan.

- assess potable water storage which have a higher inherent risk of supply failure and are likely to require tankered volumes of water to maintain supplies. The company should ensure that access and connection arrangements are adequate including provision of hard standing for parking tankers

- The company should review its access routes to critical assets and make arrangements with Roads Service to request that routes are salted to maintain access under frozen conditions.

- Review Water Resources Management Plans to include a critical period assessment covering peak winter demands. Work with other stakeholders to assess the likely occurrence and impact of peak winter demand and develop a rational, risk-based approach to this issue.

- Continue to assess the hydraulic capacity of the existing and planned trunk mains drawing on the experience gained of operating at full capacity over a sustained period. Assess the resilience of the trunk main network and work with other stakeholders to define appropriate levels of service in consultation with consumers

- Review the capacity of its potable water storage in detail to identify individual reservoirs which do not have sufficient capacity to reduce the risk of service failure to acceptable levels. The assessment should consider the risk and consequential impact of supply failure resulting in a clear statement of need. The assessment should take account of the resilience of the supply arrangements and an appropriate level of service informed by consumer views and developed in conjunction with policy makers and regulators

- Recognise that extreme weather conditions can have an impact on the performance of treatment plants. It would be expensive to design plant to secure performance in all circumstances. Attempting to do so can result in plant which is so large that it is detrimental to normal operation. Policy makers and regulators should consider their requirements for the company to design for all circumstances and ensure that design standards, consents, licences and regulatory action take account of the costs and benefits of investing to deliver full compliance in all circumstances.1.5

H3 Measures for all incidents

- Collaborate across company boundaries, including with NAVs, to ensure that customers experiencing supply interruptions received water.
- Have an up-to-date, comprehensive communications plan.
- Focus appropriately on the most vulnerable customers and sites, such as those on the high priority register.
- Ensure that customers entitled to compensation received their payments promptly.
- Ensure priority service registers are fit for purpose to support vulnerable customers, comprising accurate and up-to-date customer contact information and details of customers' individual needs.
- Proactively communicate with customers across multiple channels so customers are kept up to date, receive accurate information, and know when issues are likely to be resolved.
- Ensure alternative water supplies are readily available, with bottled water stations distributed in accessible locations for all customers and ensuring the most vulnerable customers are properly supported.
- Ensure all vulnerable customers receive alternative water in the timescales stated within the emergency planning guidelines.
- Follow the reporting guidance in Annex A of the emergency planning guidance.
- Make use of social media and local area webpages on water company websites to keep customers informed.
- Escalate incidents as necessary according to the company's escalation procedure.
- Deliveries of bottled water are recorded to enable verification that requirements have been met.
- Where bottled water stations are used, the locations of these should be inclusive and suitable for the customers affected.

- Contingency plans are up to date to ensure that treatment assets and sites are resilient and that critical failure points are identified and fed into risk assessments.

- Protection of supply to key sites should not be at the expense of large numbers of customers. For example, closing off supply to large DMAs should be considered as a last resort. Contingency plans should be regularly reviewed to ensure they are fit for purpose to ensure this.

- Communications should show empathy, recognising that incidents can be very stressful and difficult for people to manage and should provide reassurance throughout the stages of the incident

- Explanations should be clear, detailed and easy to understand, avoiding complex, technical terminology and jargon.

- Communications should be realistic and not raise expectations of affected customers unreasonably.

- Using complaints analysis to increase their understanding of the customer experience during and following incidents, and improve their readiness for future incidents

- Introduce tailored approaches for repeatedly failed customers, such as cancelling bills

- Companies should offer a genuine apology and explanation for any service disruption experienced, even if the root cause was out of the company's control.

- Companies should work together to share experiences of how they have managed incidents and supported customers in order to continually learn and improve.

- Companies should provide clarity over the services that customers on the PSR will receive for their specific circumstance.

- Companies may choose to have go above statutory minimum payments to customers to reflect the level of disruption experienced.

- Adopting a common industry approach to preparation, sharing of information and best practice in a number of key areas related to emergency response and share best practice between companies regarding emergency response.

- Consider how to improve the co-ordination and the sharing of information between wholesalers, retailers and business customers in emergency situations.

Appendix I Hydraulic modelling resilience and sufficiency metrics

I1 Entropy approaches

Entropy, also known as flow paths-related indices consider the level of redundancy in the system by assessing its connectivity.

I1.1 Flow entropy

Flow entropy quantifies the possible flow paths that water can take from sources to demand nodes, reflecting both the number of alternative routes and the uniformity of flow distribution across those routes. A higher flow entropy indicates a network with more alternative, equally important supply paths and more balanced flow distribution, which generally translates to greater resilience and reliability. Studies have generally found that, in itself, it's not a good and consistent indirect measure of network reliability.

I1.2 Diameter sensitive flow entropy

Diameter sensitive flow entropy (DSFE) modifies the flow entropy calculation by adding a term that accounts for the velocity in each pipe considering both flow and diameter reflecting the fact that larger diameters tend to have lower velocity and higher reliability. DSFE was found to be worst performing of surrogates tested (Huang, et al., 2024) (Creaco, et al., 2014).

I1.3 Mahmoud's resilience metric

Mohammed proposed a resilience metric which takes the probabilistic approach of the probabilistic resilience index (assessing the probability of satisfying nodal demands and pressure heads for various possible pipe breaks in the water distribution network at any given time) but applied the method to entropy methods. The minimum cut-set[23] approach is usually applied in order to investigate the topology of a network and the detection of its critical elements (those which would cause system failure). The method finds all possible paths from the source node to the demand node and extracts the minimum cut sets from the matrix of paths. 'Adequate supply' was defined as at least one link connecting a pipe to the rest of the network which means that a single component/asset failure does not cause system failure. This model requires

[23] Minimum cut-sets are 'a set of system components (e.g. pipelines) which, when failed, cause system failure; and when system failure will not occur if any one of those components does not fail' (Su et al. 1987).

very detailed historic break data of all the components including pipes. (Mahmoud & Piratla, 2018)

I2 Energy approaches

Energy or pressure indices consider the level of spare capacity in a system to respond to issues. The rationale is that WDSs lose energy in failure events (higher demand or component failures) and that 'spare' energy in the system will compensate to maintain levels of service in the event of a failure.

Studies have generally shown energy-based measures to perform better than entropy-based ones. Energy-based measures were more consistent with reliability and cost than entropy-based ones (Huang, et al., 2024) (Creaco, et al., 2014).

I2.1 Service reduction ratio

The ratio of minimum level of service at a threshold pressure to the full-service capacity indicates how much service reduction occurs at a threshold pressure supply level. The minimum level of service becomes 0 if the system completely stops functioning at the threshold pressure. High values indicate a highly resilient system where there is a low reduction of services, denoting a highly resilient system. (Amarasinghe, 2014) Limitations of this metric include defining what threshold pressure (system shock) should be used to calculate the metric and the challenge of calculating the minimum level of service at this pressure which will generally require running a hydraulic model.

I2.2 Hydraulic serviceability index

Total available flow / total required flow where a value less than 1 represents a shortfall in supply. The index reflects the ability of a system to deliver the flow demanded by customers under all conditions. (Markov, 2021)

I2.3 Surplus head

Wright et al advocates the use of minimum allowable head. This can be metricised as the reserve capacity with a value below 1 indicating insufficient supply to meet demand as the hydraulic resilience index. At the specified service level. In order to apply this to the network they assumed a service head of 28 m. They assumed a relationship to adjust demand based on pressure allowing the hydraulic resilience index to be calculated as the product of flow and hydraulic head across nodes. Also required is the number of nodes in the network, number of reservoirs, outflow from each reservoir and the hydraulic head of each reservoir. (Wright, et al., 2015)

Similarly, (Atkinson, et al., 2014) suggests you consider the minimum lowest nodal pressure difference between the required and observed pressure.

It's been suggested that reliability should consider both pressure and flow (Nair & Meyyappan, 2024): a reliability metric should decrease if demand is met at reduced flow, but also if pressure is adequate but demand is not satisfied.

I2.4 Available power index (API)

The API quantifies the amount of hydraulic power delivered to customers relative to the total power supplied by the system, showing how much of the supplied energy is used to meet customer demand as opposed to being lost. High values of API implies a reliable and efficient network. (Jeong & Kang, 2020)

I2.5 Resilience index

The resilience index is used to assess reliability and robustness of water distribution systems by quantifying the ability to cope with stresses on the network while meeting demand and the required pressure. This metric is derived from surplus head: the ratio of surplus hydraulic power available at demand nodes to the total power supplied to the system (minus the minimum required power to meet demands at minimum pressure). (Creaco, et al., 2014) A similar metric is system hydraulic assessment (SHA), referred to as redundancy (REDU) by Huang2024.

I2.6 Network resilience index

The network resilience index (NRI) seeks to reflect system robustness by considering both the probability of disruptions and consequences and the speed of recovery. It calculates how much of the network's demand is lost when a specific component fails, normalised by the total network demand during the event. The network resilience index is the minimum value of this metric across all components.

I2.7 Probabilistic resilience index

The pipe resilience index (PRI) extends the resilience index approach by incorporating failure probabilities of pipelines. The probabilistic resilience index is a performance-based metric designed to quantify the resilience of distribution network by explicitly accounting for the uncertainty and variability in system performance as a result of hazards and perturbations. It calculates the likelihood and extent of service disruption across a range of possible scenarios by calculating the proportion of population who experience water outages (or the proportion of water supplied to total demand) for each scenario and aggregating the results. (Kammouh, et al., 2020)

I2.8 Other metrics

There are a number of less well-established metrics that have been proposed by academics. These include

- Dracup's resilience metric (a monthly/annual metric which compares demand and delivery, reducing the metric for every node where demand exceeds delivery) (Dracup, et al., 2005)

- Berardi's reliability indicator (ratio of delivered demand to required demand at all nodes considering failure probability) (Berardi, et al., 2021)

- Nair's hydraulic reliability index (function of pressure, required outflow, required pressure and minimum pressure) (Nair & Meyyappan, 2024)

I3 Combined energy and entropy metrics

An example of combined energy and entropy metrics are the combined entropy-network resilience index (CENRI or CERI). It is calculated as a weighted average of (normalised) entropy and (normalised) resilience index. However, weights are usually set equal meaning that it is just a simple average of the two metrics. Huang et al notes that CERI has been found to be sensitive to network topology (Huang, et al., 2024).

The concept of requiring both energy and entropy was also explored by Dasic2003 who defined sufficiency as meeting the following conditions

1. The node under consideration must be physically connected to a source node (reservoir, source) (this probability is the mechanical reliability of the system).

2. The pressure in the node must be greater than a minimum required pressure. (The probability of that could also be called "system flow reliability") (Dašić, 2003)

I3.1 Pipe hydraulic resilience index (PHRI)

The pipe hydraulic resilience index (PHRI) extends the PRI by incorporating availability using what the author calls a 'probabilistic nodal connectivity' weight to the buffer energy available at each node. (Liu, et al., 2017)

I3.2 Modified resilience index

The modified resilience index (MRI) considers both surplus head (as a measure of redundancy) and uniformity of pipes connected to each node (as a measure of reliability) to estimate resilience. (Creaco, et al., 2014)

I4 Comparing hydraulic modelling metrics

The previous sections have shown that there are a large number of different metrics that have been devised. Some authors have set out to compare effectiveness and performance of such measures. Key findings are summarised below.

- Measures such as REDU and PHRI which consider only nodal energy perform worse on larger networks suggesting that it's important also to consider the distribution of pipe diameters. (Creaco, et al., 2014)

- Mahmoud & Piratla summarises early work by Raad et al. 2010 which found that the resilience index fared better than flow entropy and network resilience index at handling demand uncertainty, while network resilience and mixed reliability indices performed under pipe failures. Flow entropy was found to perform worst (Mahmoud & Piratla, 2018)

- Mahmoud & Piratla also summarised work by Baños et al. 2011 which compared RI, NRI and MRI considering pressure received by nodes under hydraulic shocks. Network resilience and modified resilience indices were found perform better overall than the resilience index. (Mahmoud & Piratla, 2018)

- Creaco et al used the demand satisfaction rate to compare indices. It found that energy approaches like RI and NRI gave a better estimate of reliability than the entropy. They also suggested that entropy may not be a useful measure of the network's capability to perform post failure. (Creaco, et al., 2014)

- Huang et al found NRI to perform best of surrogates tested, particularly suitable for designing medium scale networks but that PRI was more suitable in the low to moderate cost range. (Huang, et al., 2024)