Part I

Water Management Concepts and Principles

Chapter 1

Pathways towards sustainable and resilient urban water systems

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1.1 INTRODUCTION

Urban Water Infrastructure (UWI) plays a central role in safeguarding water security and public health and welfare. Its main functions include abstracting, treating and delivering drinking water to communities and cities, collecting and treating wastewater to a standard before it can be safely discharged into a receiving water body, and collecting stormwater to prevent urban flooding. Traditionally, UWI consists of water supply systems, water distribution systems, water treatment works, urban drainage systems and wastewater treatment works; these systems were gradually built into a city and were generally designed, operated and managed in isolation without considering their interdependencies and wide impacts on the economy and society.

Nowadays, the function of UWI goes far beyond providing water and wastewater services in cities. The potential value of blue green infrastructure, which is part of the UWI, is recognised in climate change adaptation, reduction of heat island impacts, improvement of biodiversity, and community amenity. UWI also plays a key role in reduction, reuse and recovery of resources through optimisation of the water-energy-materials nexus, helping embedding a circular economy in our society. In the era of big data and artificial intelligence, UWI digitalisation is an

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essential component in the development of smart cities. However, operation and management of UWI systems are faced with huge challenges in population increase, urbanisation, climate change, stringent regulation and aging infrastructure (Larsen *et al.*, 2016; Yuan *et al.*, 2019). These challenges are explained in more detail in Chapter 2. The future UWI needs to meet the ever-evolving societal needs and challenges to achieve resilient and sustainable water management.

While it is difficult to define what the next generation UWI looks like, it is possible to identify the potential pathways that can lead to the future UWI. This chapter aims to provide such pathways from analysing the historical evolution of urban water systems. These pathways form a roadmap that provides a broad guide on the development of UWI. The Safe and SuRe framework is then introduced for intervention development that aims to transform existing water systems to sustainable and resilient ones.

1.2 THE EVOLUTION OF URBAN WATER SYSTEMS

Historically, UWI has evolved with the increasing needs of our society, as demonstrated in Figure 1.1, which shows the transitions framework for urban water management proposed by Brown *et al.* (2009). Though this framework was developed in the context of Australia, it represents a general transition pathway for cities moving towards sustainable urban water management.

From Roman times, water infrastructure was built to provide drinking water to growing cities such as Roman aquaducts. This is the stage of 'water supply city'

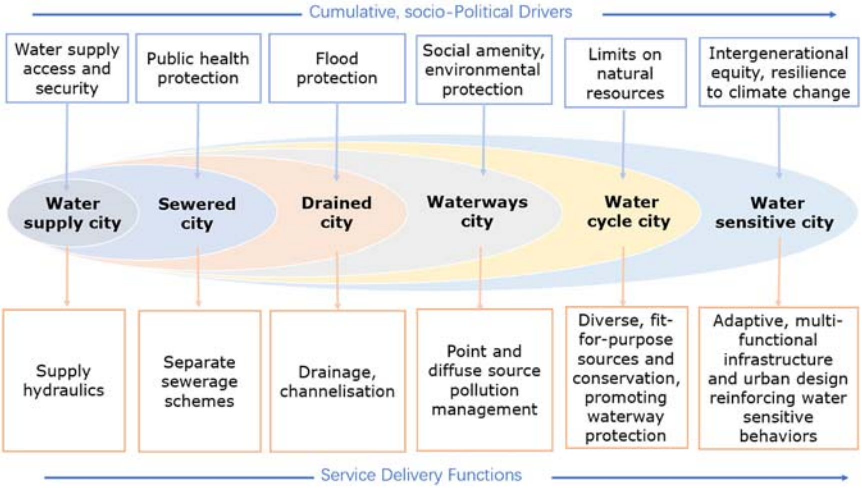

Figure 1.1 The transitions of urban water infrastructure (adapted from Brown *et al.*, 2009).

which aimed to provide water security for city residents. The Romans also built artificial drains, amongst which the most well-known is the cloaca maxima, built to drain the Roman Forum into a river (Butler & Davies, 2010). Only after the 19th century, however, did the extensive sewer system begin to be built in cities to tackle deteriorating public health problems such as outbreaks of water-borne diseases (e.g., cholera and typhoid) due to rapid population growth in cities (Burian *et al.*, 2000). This is the stage of 'sewered city' with a focus on the protection of public health. For example, in London, flush toilets discharging to cesspits became common around 1770–1780, however, connecting cesspits to the sewer system remained illegal until 1815 (Butler & Davies, 2010). This resulted in a serious health problem when the population of London expanded to more than one million. The only solution was to allow cesspit overflow to be connected to the sewer system. However, this moved the problem to the River Thames, which became heavily polluted by the 1850s. Following the great stink in 1858, an interceptor sewer system was built to take wastewater to the Thames Estuary, downstream of the main urban areas. Obviously it did not completely solve the problem but simply moved it downstream, polluting the estuary and its banks. This pollution problem started to improve only when biological wastewater treatment began to be built in the 1920s.

In the next stage of water system evolution, the separate sewer system was built to remove stormwater to tackle urban flooding which had become a high risk for many cities due to significantly increased impervious areas and population densities. As early as in the 1840s, Edwin Chadwick suggested the idea of separate systems, where wastewater is separated from surface runoff, to solve the River Thames pollution problem (De Feo *et al.*, 2014). However, at that time, it was impossible due to the complexity and capital costs of the dual system. It started to be adopted and implemented in practice in developed countries only after the 1940s. It was a period of rapid population growth and urbanisation following the Second World War, which significantly increased the risk of flooding in cities. This is referred to as 'drained city', which aimed to protect the city from flooding by quickly transporting excess stormwater downstream.

The 1970s saw a rapid environmental movement around the world, as many people worried about environmental catastrophe following substantial urban expansion of several decades. In urban water management, the focus was on reduction of pollutant discharges into water bodies and green measures such as wetlands, and bio-retention systems began to be developed and implemented in urban areas. The environmental movement eventually led to the development of the concept of sustainability in the 1980s. In this period, Sustainable Drainage Systems (SuDS) were developed in the UK as a new approach for urban stormwater management, aiming to achieve sustainable development. SuDS design generally considers achieving the benefits from four categories: water quantity, water quality, amenity and biodiversity. The concepts of waterways city and water cycle city reflect the concerns on environmental protection and limits of natural resources, respectively.

Water Sensitive Urban Design (WSUD) was a concept initially developed in Australia and accepted in many other countries. With WSUD, *water is given due prominence within the urban design process through the integration of urban design with the various disciplines of engineering and environmental sciences associated with the provision of water services including the protection of aquatic environments in urban areas*, according to the definition by Wong and Brown (2009). Building on waterways city and water cycle city, water sensitive city integrates urban water management with the natural and built environment and seeks to maximize opportunities for living with and exploiting the supply, use, reuse and management of water and stormwater to enhance and support human health and well-being by minimising the impacts of urbanisation on the natural environment and water cycle (Ashley *et al.*, 2013).

Sedlak (2015) presented a different revolution-based pathway for urban water management, largely driven by tackling human crises through technological advances. The first revolution was the development of the drinking water *supply* system, that is, the first generation of Urban Water Infrastructure (UWI 1.0) to meet the growing water demand in cities. The second revolution was the development of the drinking water *treatment* facility (UWI 2.0) using technologies such as filtration and chlorination to address the public health crisis in the late 19th and early 20th centuries. The third revolution was the invention and deployment of the wastewater treatment facility (UWI 3.0) as exemplified by activated sludge process to protect the environment. Chapter 2 provides more information on the historical development of water treatment and wastewater treatment technologies. The incoming fourth revolution is to achieve self-sufficiency through diversified water sources such as grey water, stormwater, and seawater. Again, this will be driven by developing new treatment technologies to meet stringent water quality standards.

1.3 PATHWAYS TOWARDS SUSTAINABLE WATER SYSTEMS

While it is difficult to be specific about the characteristics of future urban water systems, several general trends have become clear through research and practice in the last several decades: decentralisation, greening, circular economy, and digitalisation. These could be regarded as the pathways leading towards sustainable urban water systems (Figure 1.2) and are discussed below.

1.3.1 Decentralisation

Centralisation has been the key design principle of urban water systems from Romans water supply to modern urban water systems. In a centralised system,

Figure 1.2 Pathways towards sustainable urban water systems.

water is often taken from a long distance and distributed from water treatment works (WTWs) at high pressure over a large area; and wastewater and stormwater are collected again for centralized treatment. Centralised systems, which are currently the normative and predominating paradigm in developed countries, can achieve cost savings in capital investments, operations and maintenance based on the theory of the economy of scale. In a centralised system, however, water, energy and materials may be unnecessarily lost, wasted and misused. For example, over 3 billion litres of water, which is about 20% of water consumption, is lost daily through leakage in the water distribution systems of England and Wales (Consumer Council for Water, 2019). Similarly in sewer systems, some pumping is unavoidable in many cases to divert wastewater to a centralised treatment plant, though collection and conveyance of wastewater mostly rely on gravity-based systems.

Decentralised systems have been regarded by many as a new paradigm for the future water system (Arora *et al.*, 2015). In a decentralised system, water is supplied from local and diversified sources and wastewater is treated within individual houses, buildings and communities. The key feature of decentralised systems is the use of regional or local facilities for water supply and wastewater treatment without long-distance transport and large-scale facilities (such as water treatment, wastewater treatment and pumping stations) so that they are more flexible than centralised systems to adapt to future uncertainties such as environmental change. Water supply self-sufficiency can be achieved with locally available water sources through improved water use efficiency, stormwater harvesting, greywater reuse, and recycled water. Decentralisation represents a pathway to the fourth urban water revolution envisioned by Sedlak (2015).

There has been much debate on centralised versus decentralised systems (Makropoulos & Butler, 2010). It was argued that decentralised wastewater systems would have the same capital, operating and maintenance costs as centralised systems to achieve similar levels of service (Ho & Anda, 2006), though decentralised systems are generally thought to have a greater energy and carbon footprint. Decentralised systems have many economic, social and environmental benefits, such as water saving through leakage reduction in large water distribution networks, flexibility in adapting to changing environments, lifestyle enhancement due to private green space and property value, and reduction of overflows. It is also suggested that decentralisation promotes local re-use of water and thus increase water productivity (Larsen *et al.*, 2016). However, there are many challenges in developing decentralised systems, such as spatial integration of such systems, energy intensity, social resistance from the public, lack of clear legislation, lack of clarity on responsibilities and liabilities (Arora *et al.*, 2015).

Technological advances will make decentralisation more feasible. On-site water and wastewater treatment can now achieve high water quality standards. For example, ecological wastewater treatment systems (e.g., wetlands and biofilters) and package biological plants have been applied in many countries in the world to treat residential, industrial, and municipal wastewater. Large-scale applications of these systems could potentially reduce the costs and improve system performance significantly.

1.3.2 Greening

The idea of green urban structures can be traced back to the concepts of urban farming and garden allotments in the 1870s (Pötz & Bleuzé, 2011). It is only since the 1980s, however, that concepts and terminologies, which highlight the importance of the use of nature-based solutions, have begun to emerge for urban water management, specifically in the area of urban stormwater management. The most common terminologies include low impact development (LID), Best Management Practices (BMPs), sustainable drainage systems (SuDS), water sensitive urban design, Urban Green Infrastructure (UGI) or Green Infrastructure, Blue-Green Infrastructure, the Blue-Green City (Thorne, 2020) and the Sponge City. These terminologies were developed in different countries and contexts and have different focuses and scopes, however they are all based on the same broad principle: mitigating the impact of urban developments through mimicking nature and achieving wider benefits than water quantity and quality (Fletcher *et al.*, 2015).

UGI has a very board scope far beyond water management. The concept of UGI originated from the field of landscape architecture and ecology in the USA in 1990s; it has been promoted as a network of near-natural and designed spaces and elements in cities, planned and maintained in such a way that the infrastructure as a whole offers high quality in terms of utility, biodiversity and aesthetic appeal while also delivering a broad range of ecosystem services. Indeed, the following strategic objectives are normally considered in developing UGI: improving health and quality of life, conserving biodiversity and ecological integrity, promoting social cohesion and inclusion, enhancing community resilience to environment change, boosting local economic development and attracting businesses. In a sense, it provides ecosystem services to urban residents through the value of green space.

In the field of urban stormwater management, UGI is defined as '*a network of decentralized stormwater management practices, such as green roofs, trees,* *rain gardens and permeable pavement, that can capture and infiltrate rain where it falls, thus reducing stormwater runoff and improving the health of surrounding waterways*' (Foster *et al.*, 2011). UGI is now widely accepted as part of UWI and implemented worldwide. It represents an approach that can adapt to local circumstances and address local concerns. In practice, it is common that the focus and strategic objective of UGI could vary significantly in different regions and countries. For example, it is mainly used for water scarcity management in Cape Town as discussed in Chapter 8.

In England, SuDS is primarily promoted to reduce flood risk. The current National Planning Policy Framework requires that priorities should be given to sustainable drainage and the impact of new development on flood risk should be considered. Non-statutory technical standards set out specific requirements on flood risk of both outside and inside the development as below (Defra, 2015).

For flood risk outside the development:

> 'For greenfield developments, the peak runoff rate from the development to any highway drain, sewer or surface water body for the 1 in 1 year rainfall event and the 1 in 100 year rainfall event should never exceed the peak greenfield runoff rate for the same event.
>
> Where reasonably practicable, for greenfield development, the runoff volume from the development to any highway drain, sewer or surface water body in the 1 in 100 year, 6 hour rainfall event should never exceed the greenfield runoff volume for the same event.'

For flood risk within the development:

> 'The drainage system must be designed so that, unless an area is designated to hold and/or convey water as part of the design, flooding does not occur on any part of the site for a 1 in 30 year rainfall event.
>
> The drainage system must be designed so that, unless an area is designated to hold and/or convey water as part of the design, flooding does not occur during a 1 in 100 year rainfall event in any part of: a building (including a basement); or in any utility plant susceptible to water (e.g., pumping station or electricity substation) within the development.
>
> The design of the site must ensure that, so far as is reasonably practicable, flows resulting from rainfall in excess of a 1 in 100 year rainfall event are managed in exceedance routes that minimise the risks to people and property.'

The narrow focus on flood risk in English legislation may be useful to encourage wide adoption of green infrastructure in flood-prone cities. However, its wider benefits in improving water security, urban pollution, ecosystem integrity, carbon reduction, public health and well-being should be recognised in the planning process (Thorne, 2020). Indeed, substantial evidence shows that it is an effective way to reduce the risks of climate extremes (Royal Society, 2014). The United Nations' Sustainable Development Goals and New Urban Agenda call for increased efforts in the development of UGI to tackle urban challenges and UGI should be put at the heart of governments' policies to achieve the long-term resilience and sustainability of cities.

The challenge of moving towards greening urban water infrastructure also lies in large-scale impact assessment and implementation, in addition to legislations, cost-effectiveness and community engagement. The delivery of expected services from UGI relies on spatial integration of individual green spaces and components, as implied in its definition as a network. This should go beyond urban catchments, where the focus is primarily on stormwater and wastewater management, to include the surrounding hinterlands and wider rural catchments. Nature-based solutions have been promoted for flood and water resources management at the catchment and river basin scales; they can improve the quality of water supply sources and reduce the fluvial flood risk in cities.

1.3.3 Circular economy

1.3.3.1 The linear model

The development of UWI has been following a linear 'take-make-use and dispose' model of growth in which resource recovery and reuse are not considered in the planning and design process, as illustrated in Figure 2.3 in Chapter 2. Historically, water resources were taken from the surrounding hinterlands or across river basins to meet growing water demands in cities; wastewater and storm water were regarded as waste products which need be removed from the site as soon as possible for treatment and disposal. Even today, linear thinking is still widely used to tackle water problems in many countries. When the local water sources run dry or become polluted, water is transferred from further away. This can be illustrated using the example of China where water is taken from an ever-longer distance via inter-basin water transfer projects to supply water scarce cities (Figure 1.3).

China has constructed a large number of water transfer projects to meet burgeoning water demands from rapidly urbanizing cities and expanding economies across its 10 first-order basins (Figure 1.3a). Water is transferred mainly from the Yangtze, Yellow and Southwest River basins to the Hai, Huai and Yellow River basins. It should be noted that the Yellow River Basin delivers water to other basins while receiving water mainly from the Yangtze River. The inter-basin water transfer capacity had been steadily increasing until 2000 when a building boom occurred to meet demands from rapidly expanding cities and economies (Figure 1.3b). One of the key projects constructed was the largest South-to-North water transfer project in the world; it includes eastern and central routes, each of which covers a distance of more than 1000 km and crosses four major river basins: the Yangtze River, Yellow River, Huai River, and Hai River, with a capacity of 25 billion $m^3\ yr^{-1}$ (Ding *et al.*, 2020). As a result, in 2016, ~48.3 billion $m^3\ yr^{-1}$ could be transferred via open channels or pipelines, many of which require pump stations. This is compared to the total demand of

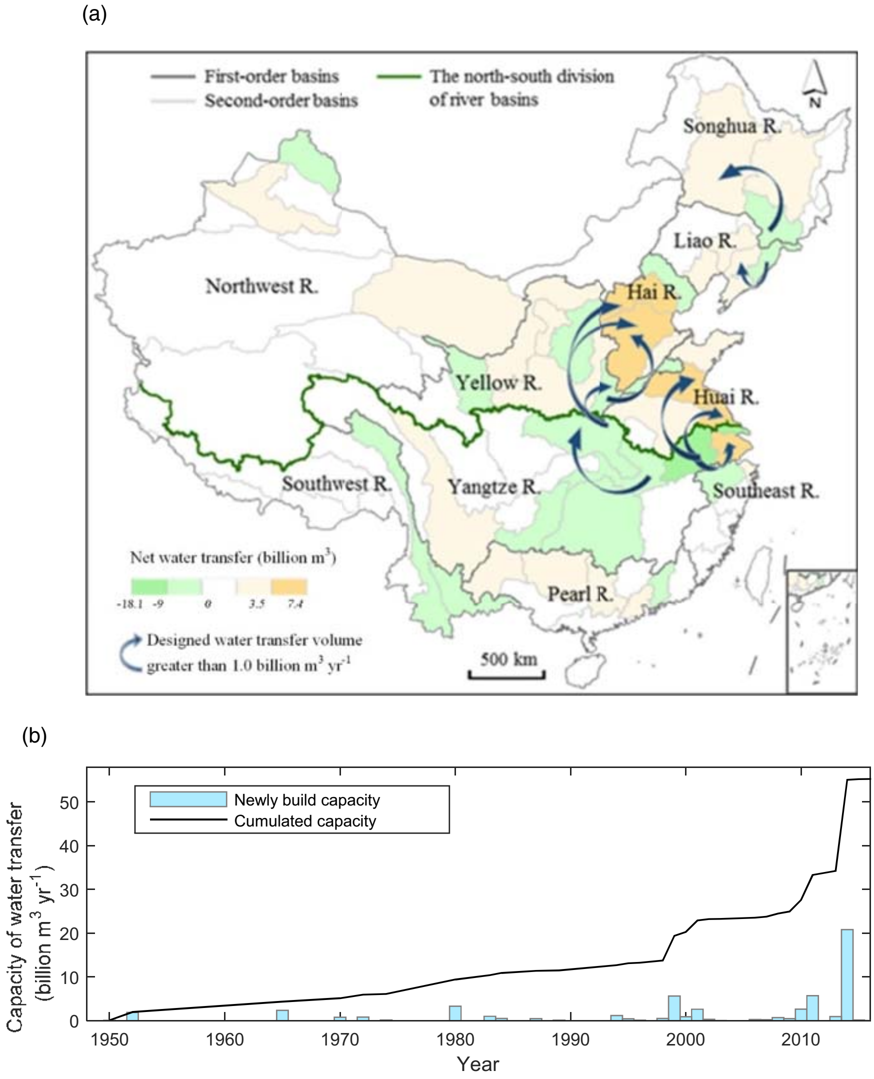

Figure 1.3 Inter-basin water transfer projects in China. (a) The water transfer volumes and directions. (b) Annual increase in water transfer capacity since 1950s.

~600 billion $m^3\ yr^{-1}$ in China, which includes residential, industrial, agricultural and ecological demands. The residential water demand was about 82.2 billion $m^3\ yr^{-1}$ in 2016. The large scale of water transfer in China demonstrates the dominance of linear thinking in the practical water management and the challenges in achieving water supply self-sufficiency in the region and river basin levels.

1.3.3.2 The circular economy model

The circular economy model, an alternative to the linear model, would turn goods at the end of their service life into resources for others, promoting reuse, recycle, repair and recovery of resources where possible. A shift to a circular economy could reduce greenhouse gas emissions by up to 70% by 2030, according to a study of seven European countries (Stahel, 2016). From the perspective of circular economy, the urban water system is defined as an integrated system of water supply, water consumption, wastewater and stormwater, where the resources including water, energy and materials (e.g., chemicals and biosolids) are used sustainably and recovered fully where possible (IWA, 2016).

The next generation urban water infrastructure, UWI 4.0, should be built on the concept of circular economy to provide a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and maximizes resource value at each component of a system by managing finite stocks and renewable flows. A key challenge is to close the resources loop in linear water systems. Figure 1.4 shows the interlinks between resources and urban water infrastructure.

The inner resources loop represents the complex interrelations between water, energy and materials. The inner loop should be viewed in the context of water-energy-environment nexus, which is one grand challenge facing humanities. The water-energy-environment nexus has drawn increasing attention in recent years as the ‘perfect storm’, where water, energy, food and environment crises could

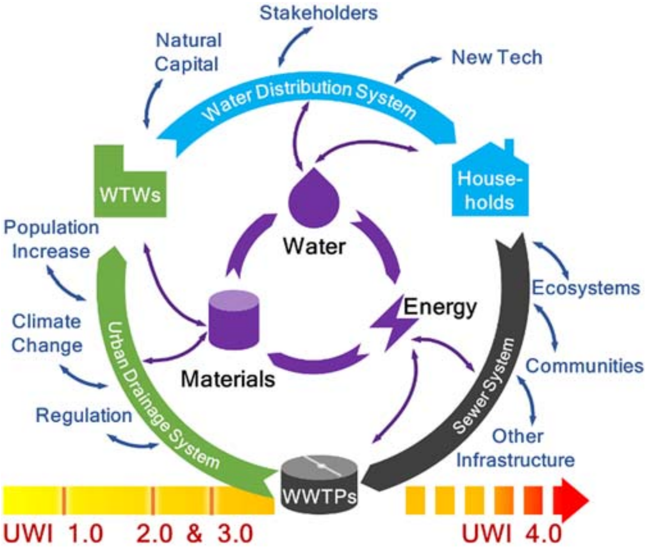

Figure 1.4 The water-energy-materials nexus with the urban water system.

occur simultaneously and thus significantly exaggerate the situation, became a concern for policy and decision makers (Olsson, 2015). The water sector is an energy-intensive sector, which consumes 4% of the energy globally. Understanding the nexus in the urban water systems is key to: (1) identify the fundamental and critical interrelations between factors; and (2) identify options to improve resource efficiency.

The outer water infrastructure loop integrates various water systems as an entire urban water infrastructure system. The outer loop builds on the integrated approach for urban water management (Butler & Schütze, 2005; Fu *et al.*, 2008). This requires a system of systems approach to consider interdependent natural, infrastructure and economic systems of different scales such as the hydrological system, land use, agricultural system, transportation system, building system, and social system (Bach *et al.*, 2014). Chapter 10 discusses the latest advances in integrated modelling and control of urban wastewater systems.

The two loops are intertwined. The architecture of water infrastructure will shape the flows of resources, while the nexus of water, energy and materials will determine the performance of water infrastructure. For example, the 'sulfide problem' in sewers, where sulfate (SO_4^{2-}) in wastewater is biologically converted into toxic hydrogen sulfide gas (H_2S) and further to corrosive sulfuric acid (H_2SO_4) under anaerobic conditions, leads to noxious odours and damage to sewer systems. Recent research reported that replacing a coagulant in the treatment of water, the SO_4^{2-} concentration in the wastewater can be reduced such that H_2S no longer affects sewer infrastructure (Pikaar *et al.*, 2014; Rauch and Kleidorfer, 2014). This example shows how the use of material in water treatment can affect the system performnace of the downstream sewers.

Understanding the two loops and their linkages is key to moving towards UWI 4.0. Research challenges remain in many areas, such as identifying key resources flows and their impacts on the nexus of water-energy-materials, characterising the UWI to maximize the reuse and recovery of resources, developing new approaches to upgrade and retrofit existing water systems. Such systems should be able to adapt to future uncertainties, while supporting both rural and urban communities and economies.

1.3.4 Digitalisation

The use of data analytics to support decisions on urban water management can be traced back to the work of John Snow in the 1850s when he analysed the spatial data of cholera victims in London to identify the source of the cholera outbreak (Eggimann *et al.*, 2017). This exemplar case illustrates the importance of data availability in tackling public health crises. Since then, data analytics has played an ever-increasing role in improving urban water and wastewater services. One of the milestones is the development and application of computer models for water management that emerged in the 1950s. This led to the establishment of a new research area: hydroinformatics (Abbott, 1991). In the early 2000s, new opportunities arose for water research communities and water utilities when deep learning technologies began to be developed and applied to a range of industries.

The Smart Water Networks Forum used a five-layer architecture to describe smart water networks (SWAN, 2020). This architecture is revised here to represent the key components of smart urban water infrastructure: physical infrastructure, sensing and control, collection and communication, data management and decision support systems, and data analytics and artificial intelligence. Figure 1.5 illustrates the five-layer architecture using the water supply system.

The physical layer consists of the grey and green structures that carry out hydrological, hydraulic, chemical and ecological functions (e.g., infiltration, storage, conveyance, treatment and purification of water, stormwater or wastewater) in the UWI system, such as swales, retention ponds, reservoirs, combined sewer overflows, storage tanks, pipes, water and wastewater treatment facilities. The evolution of the physical layer is described in Section 1.2.

The sensing and control layer consists of sensors, controllers, and actuators that carry out the remote control function. This layer is the hardware part that sits in or comes into contact with the physical water infrastructure, such as flow and pressure sensors, and remote-controlled devices. Those components (e.g., gates, valves), which cannot be remote-controlled, are part of the physical layer, as they do not have the data interfaces as part of the UWI smartness.

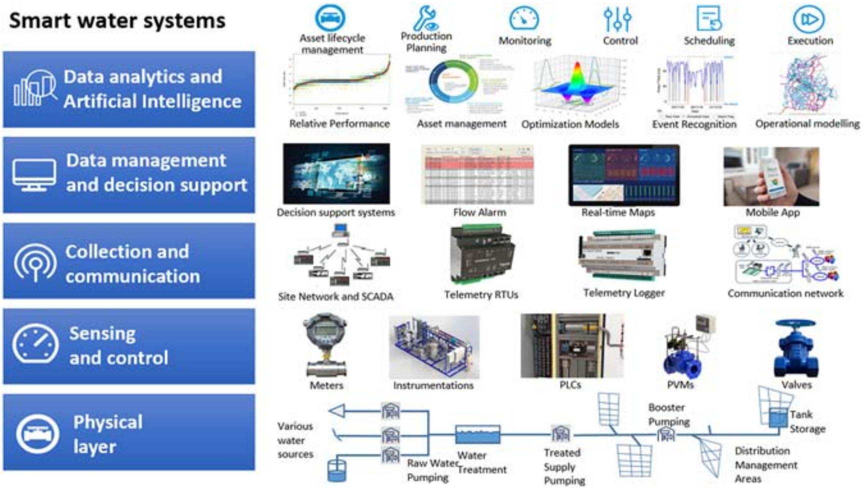

Figure 1.5 The architecture of urban water systems (adapted from SWAN, 2020).

The collection and communication layer carries out data collection, transmission, and storage functions. This layer relies on information and communication technologies such as mobile networks, satellites, and cloud data storage and thus is closely linked with cyber and communications infrastructure.

The next two layers – data management and decision support, and data analytics and AI – are the soft part of the architecture, which aims to provide optimal planning and management of UWI. It consists of databases, decision support systems, computer simulation models, machine learning and artificial intelligence algorithms.

The development of Instrumentation, Control and Automation (ICA) systems is a key part of the digitalisation pathway. ICA began to be applied in the water and wastewater treatment works as early as the 1970s (Yuan *et al.*, 2019). In the last decades, it has gained wide application in the water and wastewater industry, mainly due to the following reasons: (1) increasing pressure on the existing system capacity from urbanisation, climate change, stringent regulation, and aging infrastructure; (2) advances in the development of ICA technologies which enable real-time data collection and control while driving down the cost of ICA system installation; (3) increasing computing power that enables real-time, online optimisation; and (4) advances in the field of hydroinformatics with significantly improved modelling and predictive accuracy.

Digitalisation will not only transform how UWI is planned, operated and managed but will span into a wide range of issues including the nature of workforce operations, customer experience, and the role of the water sector in the development of smart and sustainable cities (IWA, 2019).

It should be noted that these pathways towards sustainable urban water systems are not mutually exclusive but inter-connected. For example, digitalisation can crossover all other pathways as digital solutions can be implemented to monitor and control green infrastructure, improve resource recovery efficiency through optimal control of the water-energy-material nexus, and accelerate decentralisation through autonomous operations of water systems locally and at a small scale rather than in a centralised control room.

1.4 A NEW PARADIGM TOWARDS SUSTAINABLE WATER MANAGEMENT

A fundamental question remains open: how do we know if an urban water system is sustainable? A prerequisite for this question is that the targets or ending points for sustainable water systems are known. It is been suggested that sustainability is not about the destination but better conceptualized as a journey (Butler & Davies, 2010). The four pathways discussed above provide a broad guide on the journey towards sustainable water systems. To ensure that our journey follows the pathways, performance measures are needed to assess the efficiency and effectiveness of the delivery of services from water infrastructure systems and provide an insight on where we are compared to past values, targets or other systems' performance;

frameworks are needed to develop intervention strategies to improve the system performance so that we do not move away from the pathways.

In this section, the intervention framework developed from the Safe & SuRe project is suggested as a new paradigm that enables the transformation of the existing water system towards a more sustainable and resilient one. More information can be found in the work by Butler *et al.* (2016).

1.4.1 Performance measures

It is argued that the performance of urban water systems can be broadly described within three categories: reliability, resilience and sustainability (Butler *et al.*, 2016), which are explained below.

Reliability has been at the heart of water system design and management for centuries. System reliability is defined as 'the degree to which the system minimises level of service failure frequency over its design life when subject to standard loading' (Butler *et al.*, 2016). It is generally interpreted as a probabilistic term considering uncertain design circumstances (e.g., stress and shock) and system responses which could occur within a specified design life. In the context of hydraulic reliability, the water distribution system design problem is normally to maximize the likelihood of water demand and/or pressure being met across all the nodes in the network and/or over an extended period where projected demands during normal or emergency water supply are considered. The sewer system design problem normally aims to minimize the likelihood of sewer flooding or surcharge across the network, given design rainfall events. Wastewater treatment plants are designed for the specified effluent quality being met. Reliability-based design and management aims to provide fail-safe performance. In other words, it simply aims to avoid failure as far as is (cost-effectively) possible but does not consider what happens when failure occurs.

The concept of resilience has been developed in the last decades to handle failures which occur when the system is subject to extreme shocks, exceeding the design conditions. In this context, resilience is defined as '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.*, 2016). Essentially, resilience is a measure of system performance during or after a failure event, such as, can the system fail slowly, to what extend and magnitude the system can fail, how quickly and to what level can the system recover? There are various resilience measures for water distribution systems (Diao *et al.*, 2016; EPA, 2015; Meng *et al.*, 2018; Zhan *et al.*, 2020), urban drainage systems (Mugume *et al.*, 2015; Wang *et al.*, 2019) and wastewater treatment plants (e.g., Juan-García *et al.*, 2017; Meng *et al.*, 2017; Sweetapple *et al.*, 2017). All these measures aim to minimize the magnitude and duration of failure. Note, resilience has also been interpreted in a much broader context to include system properties and institutional capacity such as preparedness, recovery, robustness, redundancy, resourcefulness, and vulnerability. Resilience-based design and management aims to overcome failure and embraces a more 'safe to fail' concept.

Sustainability is typically represented by three pillars: social, economic and environmental. Thus, it is defined as '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). This reflects the situation where many water infrastructure systems can provide services beyond their design life. For example, many sewer systems built in the Victorian era are still used today in the UK. Sustainability indicators vary greatly dependent on their purposes, contexts and users. For example, the International Water Association provided a comprehensive set of performance indicators for water supply services, which covers water resources, personnel, physical, operational, quality of service and economic and financial indicators (Alegre *et al.*, 2017). This is compared to a set of 18 indicators, grouped in the following four areas: customer experience, reliability and availability, environmental impact, and financial, which are used by the regulator Ofwat to measure the performance of water utilities in England. Sustainability aims to measure the performance at all levels, both above and below the required level of services.

Reliability, resilience and sustainability seem to cover different aspects of performance, yet are interlinked with a relationship: reliability is necessary but not sufficient for resilience, and resilience is necessary but not sufficient for sustainability. It is necessary to simultaneously consider multiple performance measures in the planning and management process (Casal-Campos *et al.*, 2015; Fu *et al.*, 2013).

1.4.2 Intervention framework

1.4.2.1 Four types of intervention

The Safe & SuRe framework for interventions development, as shown in Figure 1.6, describes the relationships between threats, UWI, impacts and consequences, and identifies four types of interventions that can be implemented to achieve long-term resilience and sustainability. A key feature of the framework is the distinction between impact and consequence. Impact describes the non-compliance degree of water services delivered by UWI, while consequences represent social, economic and environmental outcomes for a recipient from any impact.

Mitigation addresses the link between threat and water infrastructure and aims to reduce the likelihood, magnitude and duration of a threat through local or global actions. Examples include measures to reduce greenhouse gas emissions to mitigate climate change impacts which then reduce the likelihood of extreme weather, that is, an external threat to UWI.

Adaptation addresses the link between UWI and impact and is defined as any action to modify specific system properties aiming to enhance the system

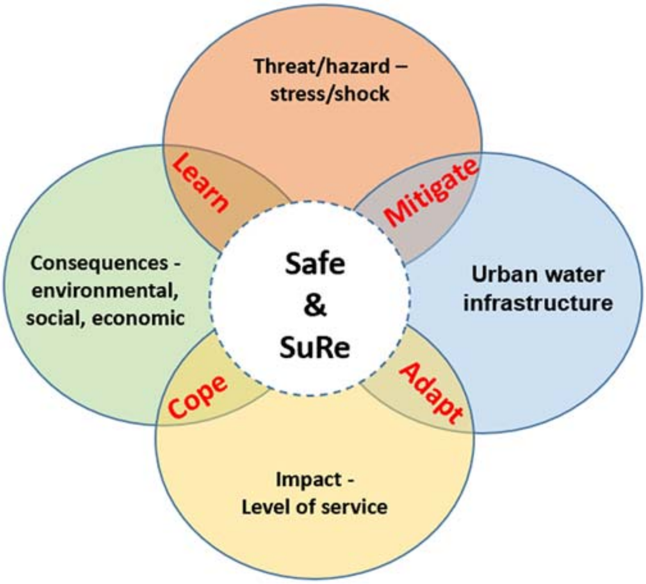

Figure 1.6 The new paradigm for sustainable urban water systems: Safe & SuRe.

capacity. It addresses the system failure that could result from any threats that cannot be mitigated. An example is use of green infrastructure to reduce urban flooding. The focus is on the UWI and its failure models, so it does not matter whether flooding results from climate change or urbanisation.

Coping addresses the link between impact and consequences and is defined as 'any preparation or action taken to reduce the frequency, magnitude or duration of the effects of an impact on a recipient' (Butler *et al.*, 2016). In an event of flooding, the consequences include damages to properties and traffic interruptions; the corresponding coping measures can be buying house insurance and taking a different route to avoid the flooded areas, respectively.

Learning addresses the link between consequences and threats, which closes the loop of the threat-system-impact-consequence chain. It aims to embed experiences and new knowledge for best practice. Examples of learning approaches include developing best practice from past events, and establishing pilot schemes to gain new knowledge or demonstrate best practice.

1.4.2.2 Analysis approaches

Distinguishing the four types of intervention maximizes the opportunity to develop effective intervention strategies. This is explicitly explored through four analysis directions: top-down, middle state-based, bottom-up and circular (Figure 1.7).

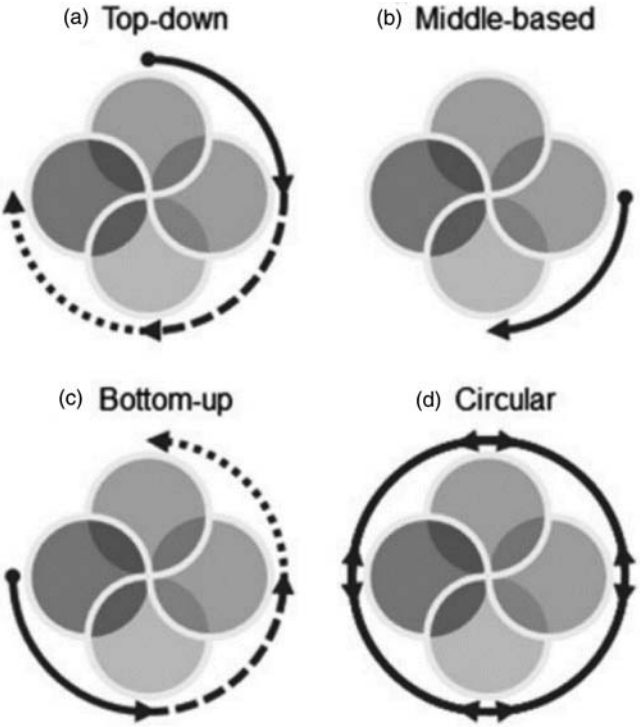

Figure 1.7 Four analysis approaches using the Safe & SuRe paradigm. Interlocking circles are interpreted in Figure 1.6. (a) Top-down. (b) Middle-based. (c) Bottom-up. (d) Circular. (Adapted from Butler *et al.*, 2016.)

The top-down approach starts from identifying and characterising the potential threats, and then propagates them through the water system to analyse the impact or consequences. This is the most commonly used approach in water management. For example, flood risk assessment is a typical top-down approach, and it assesses the consequences of hazards (e.g., rainfall events) on the water system. In practice, it is common to consider a single threat or consider different threats separately for assessment. Though there are numerous studies on characterising threats and their uncertainties, the key challenge with this approach lies in the identification of all threats, in particular, black swan (unknown) events, which are of most concern in achieving long-term resilience. Further, the top-down approach has difficulty in identifying effective interventions in the water system as their links to threats are often unclear.

The middle-based approach starts from identifying failure modes in the water system and then assesses their effects. It shifts the emphasis from identification of multiple threats to system failure modes (i.e., middle states), which are normally well-understood by domain experts. Most importantly, this makes it easier to identify interventions in response to system failure so that system performance could be improved. Compared to the top-down approach, this approach can effectively address multiple threats (including unknown events), which may result in the same system failure mode, in a single analysis. Global resilience analysis can be conducted on the basis of the middle-state approach for the water distribution system (e.g., Diao *et al.*, 2016), urban drainage (Mugume *et al.*, 2015) and urban wastewater system (Sweetapple *et al.*, 2019).

The bottom-up approach starts from identification of potential social, economic, or environmental consequences and then assesses interventions to reduce these consequences. This approach focuses on vulnerability reduction in the face of various threats and deep uncertainties and is increasingly used in water resource management in response to climate change (e.g., Poff *et al.*, 2016). It should be noted that the approach may start at either the impact stage or the system stage and proceed anticlockwise when the focus is on the water infrastructure and its service levels (i.e., impacts).

The circular approach encompasses all components of the framework with a focus on learning. When the three types of interventions, that is, mitigation, adaptation and coping are implemented in a strategy, it is important to understand their combined effects so that new knowledge could be gained and necessary adjustments to interventions could be implemented as part of the learning process.

1.5 CONCLUSIONS

This chapter analyses the potential pathways moving from the water systems of today to the next generation of systems. Four pathways are identified through the analysis of the historical evolution of urban water systems: decentralisation, greening, circular economy and digitalisation. These four pathways, which are not mutually exclusive but inter-connected, form a roadmap that provides a broad guide on the development of UWI towards sustainable water management. Three categories of performance measure, that is, reliability, resilience and sustainability, are suggested to assess the performance of water systems. The Safe and SuRe framework is then introduced for intervention development that can transform existing water systems to sustainable and resilient ones. This framework maximizes the opportunities to develop different types of interventions through four analysis approaches: top-down, middle state-based, bottom-up and circular.

Achieving smart and resilient water systems is a huge challenge. It requires an overhaul of institutional and regulatory systems, which explicitly facilitate the transformation through the Safe and SuRe framework to improve system performance. There are already many initiatives, such as Water Wise Cities promoted by the International Water Association, and many pilot cities practising along the pathways in the world, as discussed in the following chapters. This will provide valuable insight in the journey of water system transformation.

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