The changing nature of the water–energy nexus in urban water supply systems: a critical review of changes and responses

Wenyan Wu, Holger R. Maier, Graeme C. Dandy, Meenakshi Arora and Andrea Castelletti

ABSTRACT

This paper provides a review of the changing nature of the water–energy nexus in urban water supply systems (UWSSs) due to the primary long-term drivers of climate change, population growth and technological development from the 'energy for water' perspective. We identify both the physical changes in UWSSs, as well as the changes in the attributes of the system, both of which contribute to the changing nature of the water–energy nexus. We provide an overview of responses to this change in the water–energy nexus through the lens of four application areas, namely long-term planning, system design, system operation and system rehabilitation, based on the review of 52 papers. Ten responses in three categories are found to be commonly considered in each of the four application areas. The three categories are energy or greenhouse gas reduction, integrated modelling and planning, and improving social benefits. The main drivers of these responses may vary with the application area. Based on the review outcomes, we outline the gaps in the responses in relation to the changing nature of the water–energy nexus in UWSSs, providing directions for future research on improving UWSS efficiency considering the long-term drivers.

Key words | review, urban water supply, water–energy nexus

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HIGHLIGHTS

- The water-energy nexus in urban water supply systems is changing.
- The changes are mainly due to long-term drivers of climate change, population growth and technological development.
- We provide an overview of responses to the changes in the water-energy nexus through the lens of long-term planning, system design, system operation and system rehabilitation.
- Ten responses in three categories are found to be commonly considered in each of the four application areas.
- We outline the gaps in the responses in relation to the changing nature of the water-energy nexus in urban water supply systems.

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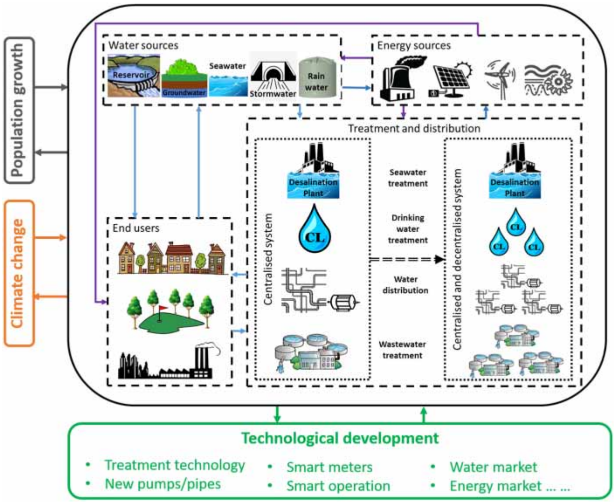
GRAPHICAL ABSTRACT



INTRODUCTION AND BACKGROUND

The relationship between water and energy is well recognised (Nair *et al.* 2014; Lee *et al.* 2017), as water is needed for energy production and energy is needed for water production and supply (Rothausen & Conway 2011; Sharif *et al.* 2019). It is also well understood that population growth is likely to lead to significant increases in water and energy demand in the future, making the availability of water one of the limiting factors enabling future energy demands to be met, and making the availability of energy one of the limiting factors enabling future water demands to be met (Carrillo & Frei 2009; Wakeel & Chen 2016), thus further strengthening this nexus. When considering the water–energy nexus, this can be analysed either by considering ‘energy for water’ or ‘water for energy’ (Nair *et al.* 2014; Vakilifard *et al.* 2018a). The majority of previous studies in this field have focussed on the latter, with the energy requirements of water systems receiving comparatively less attention (Lee *et al.* 2017). Consequently, this paper is concerned with the ‘energy for water’ side of the nexus, with a particular focus on urban water supply systems (UWSSs). As a result, wastewater systems will only be considered when they are linked to water supply through recycling.

UWSSs are an important part of the urban infrastructure system. Although the energy use for UWSSs varies significantly from city to city (Kenway *et al.* 2008), the total life cycle energy consumption of urban water systems can account for up to 7% of total energy use in a city (Wakeel & Chen 2016). UWSSs generally consist of a number of components, including those used for abstraction, storage, conveyance, treatment, distribution and end-use (Rothausen & Conway 2011; Lee *et al.* 2017). As can be seen in Figure 1, energy is used in all of these components and there have been a number of previous review papers that have focussed on the quantification of this energy usage, as well as the resulting environmental impacts. For example, Loubet *et al.* (2014), Sharif *et al.* (2019) and Lee *et al.* (2017) reviewed the use of life cycle analysis (LCA) for the quantification of energy usage in UWSSs, while Rothausen & Conway (2011) considered the greenhouse gas (GHG) emissions associated with this usage. In contrast, Nair *et al.* (2014) reviewed the concepts and state-of-the-art methods used in the analysis of the water–energy–GHG emissions nexus, whereas Stokes *et al.* (2014) and Vakilifard *et al.* (2018a) reviewed papers that considered aspects of the water–energy nexus in the optimisation of water supply systems.

The above reviews of the water–energy nexus have generally focussed on traditional sources of water (e.g., reservoirs and groundwater) and energy (e.g., coal and

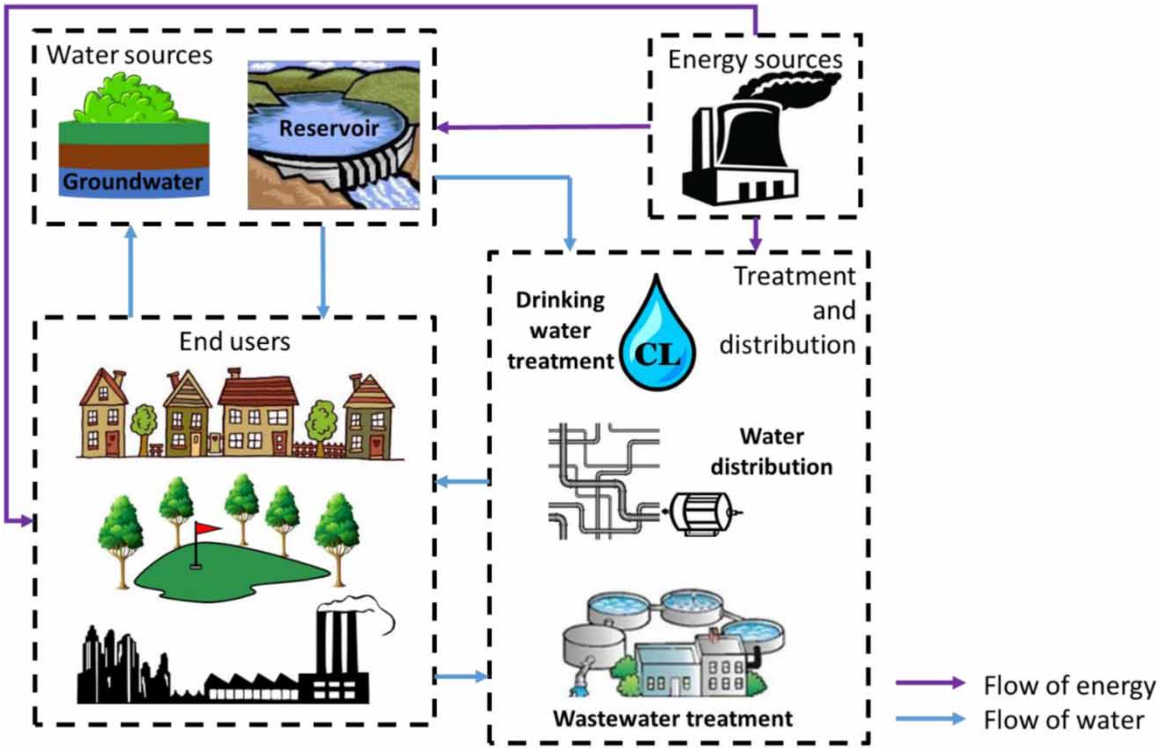


Figure 1 | Water–energy nexus in traditional UWSSs. (Note: Purple arrows show the flow of energy and blue arrows show the flow of water).

gas) production. However, these sources are changing in response to a number of long-term drivers, such as climate change, population growth and technological development (Rothausen & Conway 2011; Hamiche *et al.* 2016), resulting in the use of a range of non-traditional sources of both water (e.g., rainwater, stormwater, desalinated seawater and wastewater) and energy (e.g., wind, solar and pumped hydro) (e.g., Paton *et al.* 2014b; Guidici *et al.* 2019). This is having an impact on the nature of the water–energy nexus in UWSSs. For example, the introduction of solar and wind energy is changing energy supply patterns, which affects energy pricing and in turn impacts on the operation of UWSSs. Similarly, the use of non-traditional sources of water is a catalyst for the construction of third-pipe systems for the distribution of non-potable water supplies, which is, in turn, having an impact on both the embodied and operational energy requirements of UWSSs. While Nair *et al.* (2014) considered the energy intensity of decentralised water systems and corresponding end-uses, as well as the potential impact of the feedback loop between water scarcity and climate change, there has not been a comprehensive review of how the nature of the water–energy nexus in UWSSs is changing in response to the use of non-traditional sources of water and energy, and to what degree this has been addressed in the research literature.

In order to address this shortcoming, the purpose of this paper is to provide a framework that articulates the changing nature of the water–energy nexus in UWSSs and to provide a critical review of the papers that have described responses to this change. The remainder of this paper is organised as follows. The framework outlining the relationship between long-term drivers of change, including climate change, population growth and technological development, the corresponding changes in the provision of energy and water, as well as the resultant changes in the nature of the water–energy nexus of UWSSs, from the 'energy for water' perspective, is presented and discussed in the third section. This is followed in the fourth section by a critical review of papers that have focussed on responses to this changing nature of the nexus through the lens of the planning, design, operation and rehabilitation of UWSSs. Conclusions and future directions are provided at the end.

REVIEW PROCESS

To identify papers that address the changing nature of the water–energy nexus for UWSSs from the 'energy for water' perspective, keyword searches were conducted in the ISI Web of Science database, focussing on system planning, system design, system operation and system rehabilitation. It should be noted that this paper does not represent a systematic review of all relevant literature. Instead, the purpose is to understand how the changing nature of the water–energy nexus has been considered in UWSS-related studies, answering the following questions:

- Which long-term drivers and associated changes in the water–energy nexus in UWSSs have been considered?
- What responses have been proposed in order to address these changes and the underlying long-term drivers?

Consequently, the papers included in this review have been selected to provide a diversity of perspectives on how the changing nature of the water–energy nexus for UWSSs has been considered in the research literature. This has resulted in a critical review of 52 papers, including 9 papers on system planning, 15 papers on system design, 12 papers on system operation and 16 papers on system rehabilitation.

To enable the literature to be reviewed in a structured manner, a framework outlining the changing nature of the water–energy nexus for UWSSs from the 'energy for water' perspective is presented, as well as which aspects of this framework have been considered in the papers included in the review. The responses to the changing nature of the nexus provided in the selected papers are then critically reviewed through the lens of the framework, considering system planning, design, operation and rehabilitation, in order to identify areas with practical solutions and gaps that should be addressed in future research.

THE CHANGING NATURE OF THE WATER–ENERGY NEXUS IN UWSSS

The proposed framework outlining the changing nature of the water–energy nexus for UWSSs from the 'energy for water' perspective is shown in Figure 2. As can be seen, the framework consists of four primary components, including (i) long-term drivers of change (orange boxes), the resulting impacts on both water supply (blue boxes and

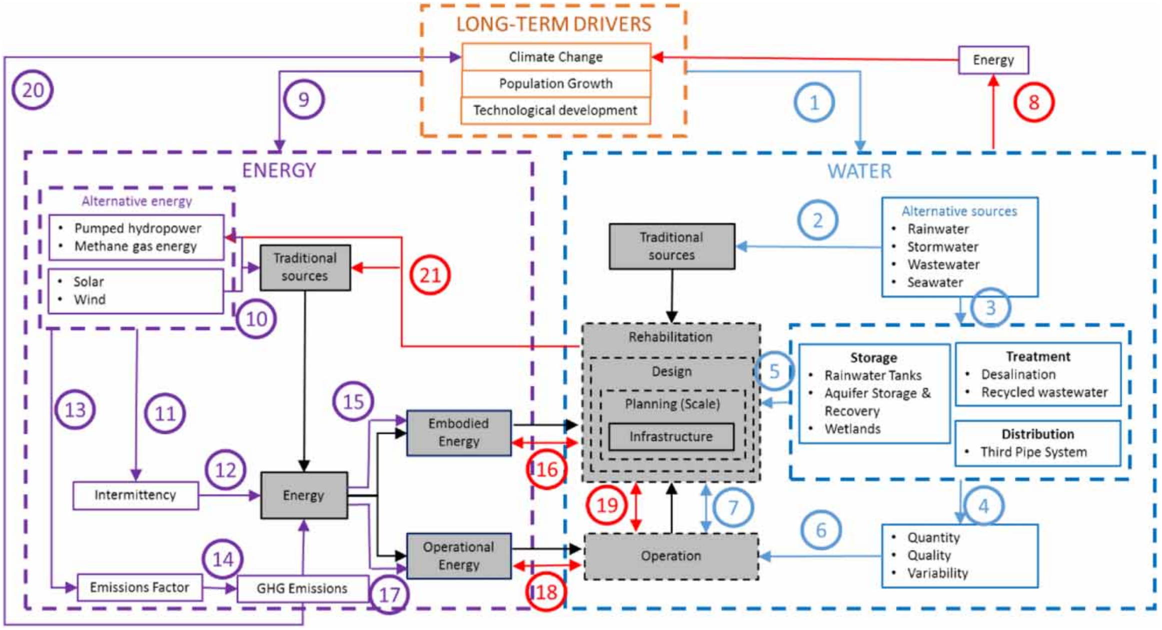


Figure 2 | Framework outlining the changing nature of the water–energy nexus for UWSSs from the 'energy for water' perspective.

arrows) and energy (purple boxes and arrows) systems and the corresponding changes in the nature of the water–energy nexus (red arrows). Each of these components is discussed in the following sub-sections.

Long-term drivers

The primary long-term drivers impacting on the nature of the water–energy nexus in UWSSs are climate change, population growth and technological development. These drivers have an impact on both water and energy supply, as indicated by arrows 1 and 9 in Figure 2. Climate change affects the water side of the nexus by increasing the variability in both water availability and demand, as well as their absolute values, with increases expected in some areas and decreases in others. In terms of the energy side of the nexus, climate change is a driver for reducing GHG emissions from energy production, but is also expected to increase energy demand (due to increased air conditioning requirements, for example). Population growth increases both water and energy demand, whereas technological development is likely to increase the feasibility and reduce the cost of both renewable energy and alternative water sources, making their use more prevalent.

Changes in water supply

As mentioned in Section 2, the combination of climate change, population growth and technological advancements has resulted in the need to consider alternative, non-traditional sources of water, such as rainwater, stormwater, recycled wastewater and desalinated seawater, to supplement/replace existing sources, as indicated by arrow 2 in Figure 2. This use of alternative water sources has led to changes in the required storage, treatment and distribution infrastructure, as indicated by arrow 3 in Figure 2. In terms of storage, the increased prevalence of alternative sources of water has resulted in the usage of household rainwater tanks to capture roof runoff, aquifers to store harvested stormwater (e.g., managed aquifer recharge) and wetlands for storing (and treating) stormwater. The use of alternative sources of water has also resulted in the need for alternative treatment technologies, such as for the desalination of seawater and the purification of stormwater, greywater and blackwater, as well as alternative infrastructure systems, such as third-pipe systems for the distribution of non-potable water.

These changes to the infrastructure components of UWSSs that have an increased penetration of alternative sources of water also have an impact on their planning, design and rehabilitation, as shown by arrow 5 in Figure 2, especially due to increased diversity in a system scale (e.g., an increase in the number of systems at cluster or household scales). However, they also have an impact on system operation, as indicated by arrows 4 and 6 in Figure 2, primarily because of an increase in system complexity resulting from (i) the need to consider the availability of different quantities of water from different sources, (ii) the need to match water quality with the end-use type, as different source waters are likely to be of different quality (e.g., potable versus non-potable) and (iii) the need to consider the temporal variability in the availability of different sources. Due to the increase in complexity in operation arising from the inclusion of alternative sources of water, there is increased benefit in including operational considerations during the planning, design and rehabilitation of infrastructure, as shown by arrow 7 in Figure 2.

Changes in energy supply

As mentioned in Section 2, population growth and climate and technological changes are drivers for the increased consideration of alternative sources of energy, such as solar, wind, hydropower and biofuels (e.g., methane), to either replace or supplement existing supplies, as highlighted by arrow 10 in Figure 2. These changes modify some of the attributes of the energy used by UWSSs, such as (i) the GHG emissions associated with their use, as different alternative sources of energy generation have different emissions factors (arrows 13 and 14, Figure 2), and (ii) the consistency of their supply, as different alternative sources of energy generation have different levels and timing of intermittency, and hence pricing (arrows 11 and 12, Figure 2).

The intermittency and changes in the levels of GHG emissions of alternative sources of energy impact UWSSs via changes in their embodied energy, which is used in the manufacture and construction of water system infrastructure (arrow 16, Figure 2), as well as their operational energy, which is used on an ongoing basis to operate water systems (arrow 18, Figure 2). There is also a feedback loop between the reduction in GHG emissions resulting from the use of alternative sources of energy and the need to introduce these sources in response to climate change, as indicated by arrow 20 in Figure 2.

Changes in water–energy nexus

As discussed previously, the introduction of alternative sources of water has resulted in a greater diversity of the water supply system, with a larger number of processes and infrastructure types with different energy demands, costs, water quality and availability. From an energy perspective, the introduction of alternative sources has changed a constant supply with fixed pricing (e.g., tariffs) and emission factors to a supply for which availability, pricing and emissions factors vary over time. The introduction of alternative sources has also resulted in increased complexity and diversity of scales, for both water and energy systems.

The above changes to water and energy systems caused by the introduction of alternative sources have a number of implications for the water–energy nexus. The fact that the different types of infrastructure associated with alternative water sources operate at different scales, not just at centralised scales, as is the case with traditional water supply systems, can create a range of trade-offs that need to be considered (arrows 16 and 18, Figure 2). For example, some decentralised systems, such as household rainwater tanks, require less energy for the collection and re-distribution of water, resulting in a reduction in embodied energy (Green 2011; Tjandraatmadja *et al.* 2013, 2015; Umapathi *et al.* 2013). However, the pumps and treatment systems used at these smaller scales are generally less efficient than those used at larger scales, resulting in an increase in operational energy (Vieira *et al.* 2014). Which scale provides the best trade-off is unknown and case study dependent. The changing nature of the energy supply associated with water supply systems that use a greater proportion of alternative sources of supply can either have a positive or negative impact on climate change (e.g., if the energy requirements of a particular alternative source is higher (e.g., desalination), then this has a negative impact on climate change and vice versa), as shown by arrow 8 in Figure 2.

The intermittency in energy supplies to UWSSs resulting from the use of alternative sources of generation results in the variation in the total emissions associated with the construction and operation of water supply systems (arrows 16 and 18, Figure 2). As the temporal variation in energy from alternative sources generally also results in a temporal variation in electricity prices, the costs associated with the operation of water supply systems also vary over time in response to the adoption of alternative sources of energy generation (arrow 18, Figure 2). Changes in the intermittency of, and emissions from, alternative water and energy sources can also result in changes in the behaviour of water end-users (arrow 18, Figure 2), affecting the magnitude and temporal variation of water demand. Another consequence of the variability and intermittency in energy supply resulting from the use of alternative sources is the increased consideration of the use of pumped hydro for the storage of electricity (arrow 21, Figure 2).

The above changes in the variability, cost and emissions associated with the operational energy of UWSSs have resulted in a number of changes in their planning, design, rehabilitation and operation (i.e. responses in relation to the drivers), as discussed in detail in the section 'The Changing Nature of the Water–Energy Nexus in UWSSs' (arrow 19, Figure 2). In addition, the desire to reduce net energy usage and GHG emissions of water systems has resulted in the use of water systems for energy production, such as the use of anaerobic digestion of sewage sludge for biomethane production (Esposito *et al.* 2012), which can be used to provide the energy needs of the treatment process itself (arrow 21, Figure 2).

A summary of the number of papers included in this review that have addressed the different aspects of this changing nature of the water–energy nexus in UWSSs from the 'energy for water' perspective is given in Table 1. As can be seen, the table distinguishes between papers that have considered different long-term drivers (climate change, population growth and technological development), different physical changes to energy and water systems in response to these drivers (consideration of alternative sources of water and energy, and consideration of different system scales and complexity) and changes in the attributes of the energy and water supplied from alternative sources (variability/changes in energy and water availability, pricing,

Table 1 | Number of papers included in this review that address different aspects of the changing nature of the water–energy nexus of UWSSs from the 'energy for water' perspective

Application area	Total no. of papers reviewed	Long-term drivers			Physical changes					Attribute changes				
		Climate change	Population growth	Technological development	Considering alternative energy sources	Considering alternative water sources	Increased system complexity	Different sytem scales	Increased demand	Varying energy/ water prices	Varying GHG emissions	Varying availability of energy/ water supply	Varying water quality	Changed user behaviour (and resulting demand)
Planning	9	6	9	4	3	9	9	1	9	0	3	3	3	3
Design	15	13	9	14	8	7	8	5	2	2	7	5	3	0
Operation	12	1	1	9	5	4	6	0	0	3	1	8	0	0
Rehabilitation	16	8	7	6	5	1	1	3	4	0	0	2	0	0

GHG emissions, water quality and user behaviour/demand). In addition, there is a distinction in terms of whether the planning, design, operation or rehabilitation of water supply systems was considered.

Table 1 shows that climate change and population growth are common long-term drivers considered together with technological development in studies on system planning, design and rehabilitation. However, technological development is the main driver for changes in system operation. Although most physical changes are considered in all application areas of planning, design, operation and rehabilitation, the different system scales (mainly resulting from decentralised systems) have not been a focus for system operation studies. The most commonly considered system attribute related change is varying availability of energy/ water supply, which is considered in all application areas; followed by varying GHG emissions, which is considered in system planning, design and operation. Varying energy/ water prices and water quality are both considered in two of the application areas. In contrast, user behaviour was only considered in system planning studies.

RESPONSES TO THE CHANGING WATER–ENERGY NEXUS IN UWSSS

System planning

UWSS planning involves defining the goals to be achieved by the system and identifying the best actions to achieve these goals. These actions are usually compiled into a water supply plan for a city or region. For example, the goals might be to supply potable water to a city at minimum cost and an acceptable level of reliability while satisfying specific environmental and social criteria. The plan would identify what water sources will be used, where the raw water will be stored, where and how it will be treated, as well as the broad layout of the distribution system for the treated water. The reliability of the system, as well as the water quality, environmental and social criteria to be met are usually also identified as part of the plan (see Appendix 3A in Dandy *et al.* 2018).

Urban water supply planning usually takes place for large centralised systems and over a long time horizon (in the order of 20–50 years). However, in recent times, decentralised systems have been developed wherein total water management, including the harvesting of stormwater and/or the treatment and reuse of wastewater, is planned at the scale of a single development or housing cluster. These smaller systems still need to be integrated into long-term planning.

A total of nine papers were reviewed that considered the water–energy nexus in UWSSs in the context of system planning. Three main responses were identified in these papers, including:

(1) Considering energy/GHG reduction as an objective (in a multiobjective optimisation framework);
(2) Developing integrated models for water and energy planning; and
(3) Developing decentralised solutions for water and/or energy production.

Figure 3 summarises these responses to the long-term drivers of climate change, population growth and technological development, including the number of papers that describe each response. Although not all papers identified all responses to each of the drivers, there was at least one paper that discussed each driver–response combination. This could be due to the nature of long-term system planning, which tends to consider all possible drivers over the planning horizon. The three principal responses are discussed in more detail below.

Considering energy/GHG reduction as an objective (e.g., via a single- or multiobjective optimisation framework)

One direct response to climate change and increased energy consumption due to increased demand resulting from population growth is to include energy or GHG reduction directly as a planning objective. The most straightforward way to achieve this is to include them in existing objectives, e.g. operating cost reduction (Vakilifard *et al.* 2019) or total life cycle cost reduction (Swamee *et al.* 2002; Lundie *et al.* 2004; Sharma & Swamee 2008). For example, Matrosov *et al.* (2015) examined the planning of London's future water supply, where energy consumption was included in the operating cost objective, together with capital cost, as well as various measures of system reliability and resilience and an environmental objective that considered how well the ecological flow of the Thames is maintained. Alternatively, a weighted sum method can be used to combine various objectives, including energy reduction, into a single-objective optimisation framework (Khan *et al.* 2018; Vinca *et al.* 2019).

Including energy/GHG reduction as an objective can also be achieved using a multiobjective optimisation approach, where the trade-offs between energy/GHG reduction and other potentially conflicting objectives, such as cost reduction, can be explored. This is primarily enabled by advances in computing hardware and optimisation algorithms, as well as in response to the increased system complexity resulting from the consideration of alternative water sources. Such an approach has been applied in a

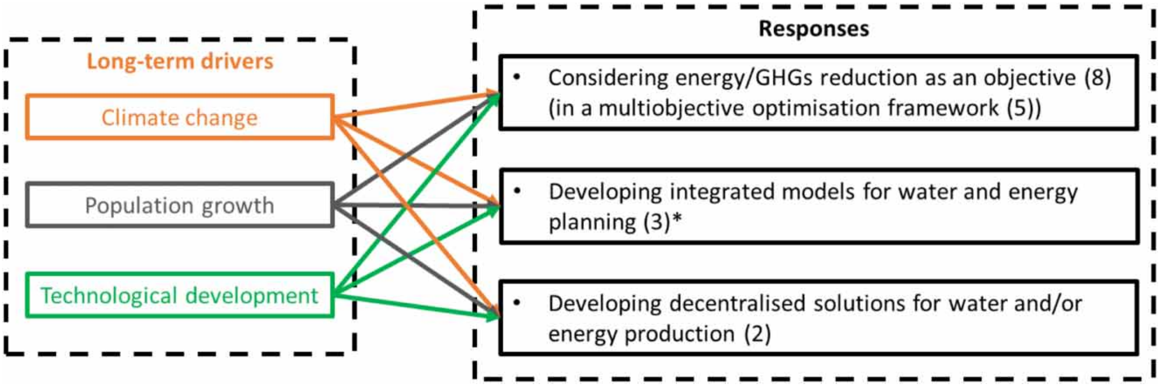


Figure 3 | Responses to changed water–energy nexus in UWSSs due to long-term drivers – system planning. (*Numbers in parentheses indicate the number of papers included the response.)

range of UWSS-related planning studies (Beh *et al.* 2014, 2015; Paton *et al.* 2014a; Wu *et al.* 2017). Wu *et al.* (2017) developed a multiobjective optimisation framework for water supply system optimisation that considers total cost, total energy, reliability and environmental impact on the receiving waters as objectives. Total energy included the embodied energy of new infrastructure, as well as operating energy, as has been investigated in other related studies (Grant & Opray 2005; Sharma *et al.* 2005, 2009). Wu *et al.* (2017) applied the framework to the Adelaide water supply system, which has various water sources, including supply from local reservoirs, inter-basin transfers from the River Murray, desalinated seawater, treated wastewater and harvested stormwater (the last two of these being for non-potable use). They showed that the minimum cost plan does not correspond to the minimum energy plan, especially considering operation into the future (e.g., to the year 2050).

Beh *et al.* (2014) and Beh *et al.* (2015) considered the optimal sequencing of UWSS infrastructure into the future based on cost, GHG and reliability objectives via a multiobjective approach. The studies considered emissions due to both embodied energy in new infrastructure and operating energy via a constant emission factor. The results demonstrated that there are trade-offs between GHG reduction and the traditional objective of cost reduction and that more flexible infrastructure planning can be achieved via the use of multiobjective optimisation to cater for future changes. A parallel study by Paton *et al.* (2014b) considered the robustness of the various solutions to exogenous variables influenced by future changes explicitly, including climate change and population growth.

Developing integrated models for water and energy planning

Another common response to the long-term drivers is to develop integrated models for the long-term planning of both water and energy systems. This response draws on alternative energy and water sources and is necessitated by the increased system complexity resulting from the use of alternative sources of water and energy. For example, an integrated optimisation model was developed for all of Spain to track energy flows throughout the life cycle of the water system (Khan *et al.* 2018). This study considered a future scenario for 2041–2070, with increased temperature and reduced precipitation due to climate change and increased demands for water and energy from population growth. The study demonstrated that the integrated approach can lead to significant savings in both water and energy consumption, with a 5.2% saving in cost, a 2.5% saving in water consumption and a 2.5% reduction in energy consumption achieved compared with using a non-integrated approach. Alternatively, water and energy systems can be integrated at the sub-city scale (Vakilifard *et al.* 2019), where integrated decentralised water and energy systems (see the next response) could save the city of Perth in Australia around $250 m over the planning horizon (2017–2031).

In addition, water and energy systems can be further integrated into land planning. Vinca *et al.* (2019) described the NEXUS solutions tool (NEST) that is a platform for optimising land–water–energy transformations, with water, energy and land sub-models interacting with each other. The energy sub-models can include all sources of water, as well as wastewater and reuse streams, and operates at a sub-basin level. The energy sub-model includes all forms of energy generation, as well as energy transmission between zones. There is also a land sub-model that models land use in a large number of categories. The interactions between the sub-models include: (a) the energy requirements of water production, treatment, distribution and recycling; (b) the water requirements of various energy generation methods; (c) the capacity for hydroelectric development and (d) the energy and water demands of agriculture, as well as other land-use activities. Vinca *et al.* (2019) applied the platform to the case of UWSS planning in the Indus River Basin for the period of 2015–2060 under various scenarios aimed at achieving various United Nation's Sustainable Development Goals.

Developing decentralised solutions for water and/or energy production

An emerging response to long-term drivers of the water–energy nexus in UWSSs is to develop decentralised systems, which is partially driven by the consideration of alternative water and energy sources due to climate change, population growth and facilitated by technological development. These alternative water and energy sources are often supported by small-scale systems, such as rooftop rainwater collection systems and solar panels. In a study by Vakilifard *et al.* (2019), the authors explored the possible use of household photovoltaic systems to generate excess energy that can be used to power desalination plants of various sizes for residential water supply. It was found that significant savings can be achieved during the planning horizon using decentralised systems compared with the use of traditional centralised supply systems. In a study by Newman *et al.* (2014), the authors demonstrated a decentralised approach to total water management at the residential district scale that considers a number of non-conventional options, such as reuse of greywater and blackwater, as well as the use of rainwater tanks. The results demonstrated that over 50% savings in water consumption from the centralised system could be achieved by using local water sources due to their competitiveness in terms of cost and GHG emissions. The scale of decentralisation was shown to have a significant impact on the effectiveness of the overall system. The trade-offs between the scale of decentralisation and overall system effectiveness remain an open research question, although a recent study took a first step towards this by introducing and testing an integrated framework for selecting and evaluating the potential benefits and costs of using stormwater harvesting systems to supplement existing centralised UWSSs (Dandy *et al.* 2019).

System design

UWSS design involves defining the layout of, and interactions between, the various subsystems needed to achieve current and future planning goals. These subsystems fall into three main categories: water source, water treatment and water distribution systems. The design of these systems will depend on the long-term planning goals. For example, if the goal is to supply fit-for-purpose water at least cost and energy input, then all water sources available at varied spatial and temporal scales need to be considered, spanning from lot to precinct scales, as well as sub-daily to seasonal scales.

A total of 15 papers were reviewed that considered the responses to the changing nature of the water–energy nexus in UWSSs through the lens of system design. Three main responses were identified in these papers, including:

1. Considering energy/GHGs reduction as an objective;
2. Integrating urban design with UWSS design and
3. Considering the design and operation of UWSSs together.

Figure 4 summarises these responses to the long-term drivers of climate change, population growth and technological development, including the number of papers (in parentheses) that describe each response.

Considering energy/GHGs reduction as an objective

One of the most significant impacts of climate change, population growth and technological development are increases in water and energy demand, leading to increased GHG emissions that further reinforce climate change. Therefore, the most direct response in system design is to include energy/GHG reduction as a UWSS design objective.

Lee *et al.* (2018) presented a framework for the overall design of UWSSs (including distribution systems) using a

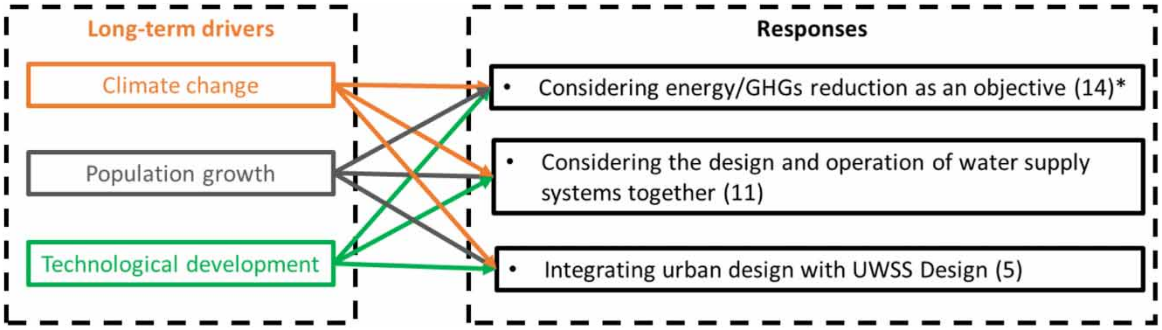


Figure 4 | Responses to changed water–energy nexus in UWSSs due to long-term drivers – system design. (*Numbers in parentheses indicate the number of papers in which this response was included.)

modified life cycle energy analysis (LCEA) method, along with a hydraulic simulation model, EPANET 2. They considered three different networks with a distinct range of pipe diameter sizes and total pipe lengths in order to evaluate the scale dependency to energy usage trend and design pathway. They showed that annual average energy usage can be reduced either by increasing the number of small pipes or extending the life cycle of the infrastructure. Zimmermann *et al.* (2018) did a comparative study to assess the relative sustainability of conventional and decentralised water infrastructure systems using an integrated assessment method. Their analysis showed that decentralised water infrastructure not only can compete with conventional ones, but can often outperform traditional systems in securing water supply, reduced energy consumption and improving environmental outcomes, especially when ecological and social criteria are emphasised. However, ecological and social criteria can be difficult to quantify and include in mathematical models. GHG emission reduction has also been included as one of the objectives in formal multiobjective optimisation approaches aimed at identifying UWSS designs that minimise both total cost and total energy usage or associated GHG emissions, especially in the context of the distribution component of UWSSs (Wu *et al.* 2010a, 2010b, 2012a, 2012b, 2013).

Alternatively, reduction in energy consumption and associated GHG emissions from UWSSs can be achieved through the use of renewable sources of energy. Giudici *et al.* (2019) proposed a novel dynamic, multiobjective optimisation approach for improving the sustainability of small islands through the introduction of renewable energy sources. This is the first time such a dynamic and multiobjective approach has been used to solve this type of problem. The authors tested their approach for Ustica Island in Italy, and the results showed that the designs using renewable energy sources outperformed the traditional design with respect to different sustainability indicators, reduced investment costs and environmental impacts.

Considering the design and operation of water supply systems together

In traditional UWSS design, the focus is often on sizing the system to achieve certain objectives (e.g., cost minimisation) while satisfying design constraints, without fully considering the impact from long-term operation (Wu *et al.* 2010b). However, the ongoing operation of these systems can have a significant impact on their performance over their lifetime, e.g. the total cost or energy consumption and associated GHG emissions over their design life (Wu *et al.* 2010b, 2013, 2017). In addition, operational conditions may vary over time due to the introduction of new technology (e.g., variable speed pumping or new treatment technologies) (Wu *et al.* 2012b; Nair *et al.* 2014), or changes in system attributes, such as varying water or energy prices and emission factors, as a result of the long-term drivers discussed previously. Therefore, it is important to have a realistic representation of system operation when designing a system with long operational lives, such as UWSSs.

Due to the development in computational tools, including simulation models and optimisation techniques, and the increased awareness of the impact of system operation on long-term design objectives (e.g., total cost and energy consumption), it is increasingly common to consider the design and operation of water supply systems together for system design (Wu *et al.* 2010a, 2010b, 2013). Marchi *et al.* (2014) provided a review of a large number of such studies. In addition, the impact of varying operating conditions due to technological development, such as the improved efficiency from the use of variable speed pumps (Wu *et al.* 2012b), and consideration of changing system attributes, such as varying energy prices (Wu *et al.* 2012a) and emission factors (Stokes *et al.* 2015a, 2015b), have also been investigated. In a more recent study, Wang *et al.* (2019) went a step further to develop an open-source integrated tool to support the integration of water–energy nexus into both the design and operation of UWSSs. The application of the tool to the sub-Saharan African metropolitan region demonstrated that by considering the energy–water nexus and multiple resource systems, water services to a growing urban population can be improved, even in the developing world where there is a lack of data.

Integrating urban design with UWSS design

Another common response to long-term drivers like population growth, climate change and technological developments in system design is the integration of urban and

UWSS design. Smith *et al.* (2018) investigated the impact of the design of water distribution systems and the layout of cities on energy associated with water supply. They concluded that the distribution of water within high-rise buildings can add significantly to energy use and should be taken into consideration when designing and regulating UWSSs. They also suggested to limit the size of the city and concentrate water demand through high density living, which leads to common green spaces, instead of individual households with small lawns. This approach has been shown to lead to significant water savings.

Lin *et al.* (2019) took one step further and investigated the water–energy nexus in urban areas. The impact of transboundary movement of water and energy due to the way cities are planned and operated can have significant impacts on the water–energy nexus, as water and energy imports can shift the burden from one region to another (Lin *et al.* 2019). With a case study in China, the authors showed that the integrated design of UWSSs, together with the design of urban areas, can improve overall system efficiency and lead to multiple benefits, such as reduced water and energy demand, reduction in the urban heat island effect and enhanced liveability outcomes. In addition, better use of waste generated from urban areas, including wastewater (and treatment byproducts) and municipal solid waste, will not only provide renewable energy, but also lead to reduced waste generation and disposal, enhanced water quality outcomes for receiving water bodies, reduced landfill areas needed for waste disposal and reduction in GHG emissions (Wang *et al.* 2018).

System operation

A UWSS incorporates a number of controllable components (e.g., pumps, valves and tanks), the position of which can be changed at a given frequency to regulate some key variables in the UWSS (e.g., pump flows, pump pressures and tank water trigger levels) in order to meet one or more predefined operating targets (Ormsbee *et al.* 2009). UWSS operation is generally designed over two different time horizons: (i) in the medium–long term, operation planning defines the operating policy to be used for the UWSS considering normal water demand and availability conditions; (ii) in the short term, real-time control specifies operation to meet changing water demand and variable water availability, typically supported by model predictive tools. Operating targets generally include costs (energy consumption and pump maintenance cost) and other technical indicators, such as demand charge (e.g., McCormick & Powell 2003; Gibbs *et al.* 2010), operational reliability (e.g., Odan *et al.* 2015) and water quality (Kurek & Ostfeld 2014). Most recently, sustainability considerations have also been included to assess the impact of operation on GHG emissions within a multiobjective context (Wu *et al.* 2013; Stokes *et al.* 2015a, 2015b).

Electricity consumption from UWSS operation is one of the largest marginal costs for water utilities and covers 70–80% of the energy consumed in a surface water-based supply system (Liu *et al.* 2012). For groundwater-based supply, the energy consumption can be even higher due to the extensive pumping and additional treatment required (if water is saline) (Copeland & Carter 2017). This water–energy nexus is projected to be even tighter in the future in response to climate and socio-technological changes as discussed previously (Vakilifard *et al.* 2018a). A number of options exist to improve water–energy efficiency in UWSSs (for a review, see Coelho & Andrade-Campos 2014). We identified three main responses in UWSS operation based on the review of 12 papers, as listed in Figure 5. These responses include:

(1) integrated management of energy and water supply systems;
(2) more efficient and flexible control of water supply systems and
(3) recovering energy from existing systems.

Integrated management of energy and water supply systems

Desalination and other energy-intensive water production technologies are being used increasingly to respond to reduced water availability and growing water demand, tightening the interdependency between water and energy in UWSSs. In this context, an increasingly explored solution is to connect UWSSs to renewable energy sources and jointly operate the coupled water–energy system in either grid-connected or off-grid mode, reducing fossil fuel dependency, and thus improving both environmental and economic sustainability of operations (e.g., Castronuovo &

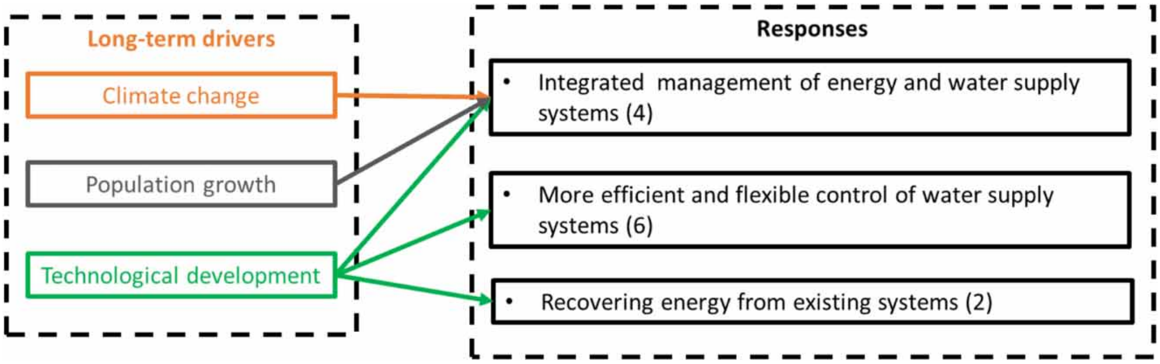


Figure 5 | Responses to changed water–energy nexus in UWSSs due to long-term drivers – system operation. (*Numbers in parentheses indicate the number of papers in which this response was included.)

Lopes 2004; Vieira & Ramos 2009; Al-Nory & El-Beltagy 2014; Mentis *et al.* 2016; Ma & Lu 2011 for a review). A large share of the literature on this topic focuses on stand-alone or off-grid systems in remote communities, such as small islands, where renewable energy source penetration has been boosted in recent decades (Erdinc *et al.* 2015) and is considered a viable and sustainable alternative to fossil fuelled generators, and water production is often extremely energy-intensive because of the presence of desalination plants (Segurado *et al.* 2015, 2016; Giudici *et al.* 2019). There are also studies that deal with grid-connected systems (Vakilifard *et al.* 2018b).

Segurado *et al.* (2016) contributed a joint operation and sizing framework for a wind-powered UWSS including a desalination plant and a pumped hydro storage. The excess wind power was used in the desalination unit and to recharge the water storage. A multiobjective problem was formulated to minimise costs, maximise the percentage of renewable energy in total power production and minimise the wind power curtailed. The approach was demonstrated on the water supply system of the island of S. Vicente, in Cape Verde (Segurado *et al.* 2015), and it was shown that in 2020, the penetration of renewable energy sources can reach 84%, with a 27% decrease of power and water production costs and a 67% decrease of CO_2 emissions. Giudici *et al.* (2019) developed a simulation-based optimisation to jointly determine the optimal size and operation of the integrated water and energy systems of the small Mediterranean island of Ustica, Italy, using a multiobjective optimisation approach accounting for cost, electricity surplus and water deficit. Better performance was found with respect to different sustainability indicators, limiting structural interventions, investment costs and environmental impacts compared with a traditional least cost approach. In particular, the optimal solutions fully covering water demand requirements allowed 40% of penetration of renewable energy sources to be reached, while substantially reducing CO_2 emissions. The potential of powering a desalination-based UWSS using grid-connected rooftop photovoltaics was investigated by Vakilifard *et al.* (2018b). The authors demonstrated that flexible (hourly) operation enabled substantial cost-saving with respect to seasonal and yearly operations, while also resulting in a nearly 20% reduction in the annualised unit cost of water production compared with the existing desalination plant in the study area.

Another advantage of integrated management of water and energy systems is that water systems can also be used to generate energy to supplement the power required by UWSSs. The operation of such a system in Taichung city in Taiwan was studied by Tsai *et al.* (2016), where the system comprised off-shore wind, conventional gas-turbine power plants and hydroelectric power plants to supply power and desalination plants, as well as water-storage tanks and reservoirs to supply water. The increased flexibility achieved by water–energy system integration allows hydrological variability and power intermittency to be exploited effectively under different water availability scenarios corresponding to different possible climate conditions. Results show that the proposed integrated approach will not only allow water demand in 2030 to be met, with more efficient use of intermittent renewable energy sources, in this case hydropower, but will also eliminate the requirement for additional gas-turbines to generate energy with natural gas.

More efficient and flexible control of water supply systems

Increasing electricity price volatility driven by renewable energy source penetration and hydrological variability induced by climate change are challenging UWSS operation planning and real-time control, with potential negative impacts on control efficiency and thus energy consumption. In most cases, UWSS systems are operated to follow predetermined water demand patterns and fail in flexibly adapting to changes in electricity prices and water demand (Coelho & Andrade-Campos 2014). In addition, most current pump systems are oversized, many by more than 20% (ibidem), representing an opportunity for more flexible and energy efficient operation control. Recent technological, such as smart sensors (Cominola *et al.* 2015), Internet-of-Things (IoT) (Stewart *et al.* 2018) and variable speed drives (Marchi *et al.* 2012), and methodological advances (e.g., machine learning and artificial intelligence) are opening up new opportunities to improve the real-time control of UWSSs to obtain not only energy efficiency, but also improved reliability, and reduced environmental impact through GHG emission reduction.

First, smart sensors allow water consumption data to be collected at very high spatio-temporal resolution/frequency, enabling very accurate water demand characterisation and prediction (Cominola *et al.* 2019). The existence of large amounts of data enables the use of data-driven approaches, such as artificial neural networks, to improve UWSS operation. For example, Guo *et al.* (2018) developed a 15-min timestep demand forecasting model using recurrent neural networks to predict water demand evolution up to 24 h ahead and showed significant improved performance compared with a more traditional seasonal autoregressive integrated moving average (SARIMA) model. Together with similar works (e.g., Donkor *et al.* 2014; Grosso *et al.* 2014; Pacchin *et al.* 2019), the study demonstrated the potential of using machine learning and artificial intelligence techniques to substantially improve our ability to inform the real-time control of UWSSs with accurate predictions of water demand.

Pumping operation accounts for the majority of operational energy consumption and associated GHG emission from UWSSs (when fossil fuelled energy is used). Significant reduction in energy consumption can be achieved if pumping operation efficiency is improved. Stokes *et al.* (2015a, 2015b) designed and evaluated a pumping control system minimising both costs and GHG emissions associated with pumping operation with time-varying emission factors (EFs) over 24-h periods. Results show that flexible strategies exist to minimise costs while reducing GHG by moving pumping to low EF times of the day. Changes in EF induced by the penetration of renewable energy sources can further increase the value of flexible pumping.

Variable speed drives introduce an additional level of flexibility in controlling UWSSs in real time. For example, variable speed drives for centrifugal pumps allow for the reduction of the number of switches (on/off) during pump operation and thus reduce pipe breaks, leading to a potential saving of 10–20% of total pumping energy (Gellings 2009). In a more recent study, Brentan *et al.* (2018) proposed a hybrid and near-real-time optimisation algorithm to jointly manage pumps working with variable speed drives and pressure-reducing valves for maximum operational efficiency. The optimisation was coupled with a near-real-time forecast of water demand to define optimal operation strategies. The approach was demonstrated using a well-known benchmark problem (D-town WDN) and showed up to 50% energy savings while enabling efficient system pressure management, thus leading to considerable leakage reduction.

Finally, advances in control methods are contributing improved real-time operation of UWSSs. Model predictive control (MPC) has been demonstrated to be one of the more promising approaches to real-time control of large-scale UWSSs thanks to its ability to adapt to quickly changing network conditions and to effectively use water demand forecasts (Creaco *et al.* 2019). However, the applicability of traditional MPC is limited by its considerable computational burden (Grosso *et al.* 2014). Sampathirao *et al.* (2018) developed an alternative method by combining an accelerated dual proximal gradient algorithm with general-purpose graphics processing units to generate computationally feasible solutions for the control of UWSSs. The approach is demonstrated on the complex

UWSS of Barcelona, Spain and showed a 15-fold increase in run time compared with traditional MPC, enabling the solution of very large UWSSs to be found in a desirable timeframe.

Recovery energy from existing systems

Pressure control is a key component of UWSS operation, presenting opportunities in energy saving from existing systems. Pressure control must be achieved by balancing the contrasting needs of keeping high pressure to ensure consistent water supply throughout the served area and to reduce pathogen intrusion and reduce pressure to reduce both leakage and the risk of pipes bursting. Pressure-reducing valves (PRVs) are traditionally used to reduce water pressure in UWSSs (Prescott & Ulanicki 2008). In recent years, pumps used in turbine mode (or pump-as-turbine (PAT)) are becoming increasingly popular for their dual purpose of controlling pressure and recovering energy, thus contributing positively to the water–energy nexus, while ensuring the key services mentioned above are able to be maintained (e.g., Du *et al.* 2017). The installation of PAT has been extensively studied in terms of design (number, size and position) (e.g., Carravetta *et al.* 2012; Muhammetoglu *et al.* 2017) and experimental analysis (e.g., Fontana *et al.* 2012), but the integration of PAT as additional controllable devices within UWSS operation planning or real-time control is relatively unexplored, though it provides an additional element of flexibility to cope with electricity price variability.

A control strategy for the automatic setting of the regulating valves in a PAT was developed by Fontana *et al.* (2016) to achieve the dual objectives of modulating pressure and maximising energy recovery. The results showed that the valves can automatically regulate the flow running the PAT and guarantee the set point pressure at the network monitored node under increasing variability and abrupt pressure changes. In another study by Lima *et al.* (2018), the authors contrasted four different control strategies for a PAT in a pressure-reducing station in Southern Italy using a stochastic model of the hydraulics feature fluctuations. The results showed that PAT can recover up to 557 kWh energy in a 24-h period for a small case study network considered, and different regulations can lead to quite different behaviour of the system, which, in turn, has an impact on plant efficiency, reliability and sustainability.

System rehabilitation

UWSS rehabilitation refers to the use of repair, renewal and replacement technologies to return functionality to the system (EPA 2007). Since most UWSSs were constructed many years ago, rehabilitation is also used as an opportunity to use new technologies to improve or expand the functionality of these systems to meet new challenges, including increased demand due to population growth and switching to renewable energy sources to reduce GHG emissions. There is also a myriad of connections between water and energy in UWSS rehabilitation, as discussed previously.

System rehabilitation is also a straightforward way of making changes to existing UWSSs in response to long-term drivers, the resulting changes and their impact. As mentioned previously, 16 papers considering the water–energy nexus within the application area of system rehabilitation were reviewed. These included five main responses in relation to changes in the water–energy nexus due to the long-term drivers considered in these studies, including

- considering energy/GHG reduction as an objective;
- considering renewable energy sources;
- recovering energy from existing systems;
- using water storage as energy-balancing storage and
- bringing benefits to disadvantaged communities.

The relationships between these five responses and the long-term drivers, as well as the number of papers considering each of the responses, are summarised in Figure 6.

Considering energy/GHG reduction as an objective

Despite the myriad connections between energy and water supply system rehabilitation, energy consumption is often taken for granted in studies on rehabilitation of UWSSs. For example, traditional pipe renewal planning is primarily based on leakage reduction (Venkatesh 2012; Gungor *et al.* 2017; D'Ercole *et al.* 2018), often measured using pipe breakage rates (Alvisi & Franchini 2009) or pipe ages (Kleiner *et al.* 2001), with energy saving as an incidental by-product. This approach directly addresses the

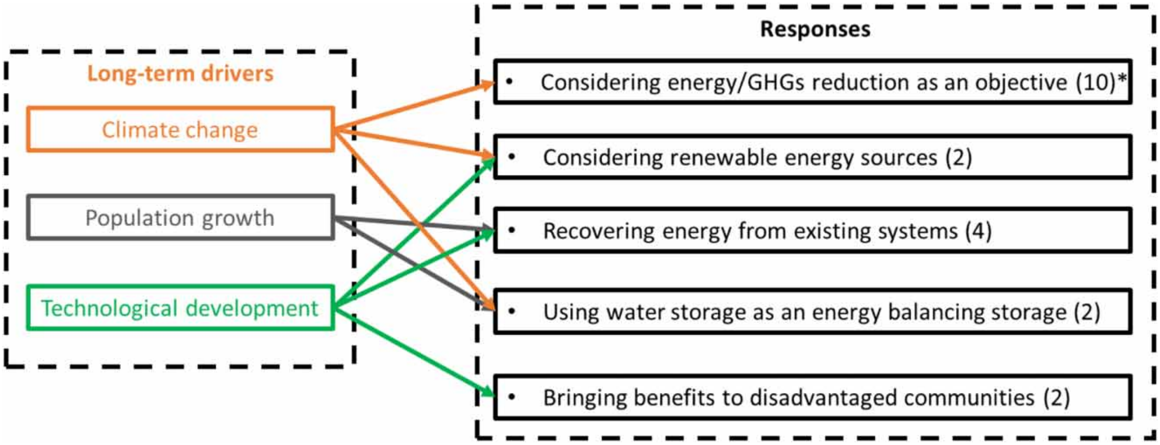


Figure 6 | Responses to changed water–energy nexus in UWSSs due to long-term drivers – system rehabilitation. (*Numbers in parentheses indicate the number of papers in which this response was included.)

driving motive for system rehabilitation, namely water losses due to leakage. In fact, up to 30% of water in UWSSs is typically lost in water distribution systems due to leakage (Kingdom *et al.* 2006). However, this approach ignores energy consumption within UWSSs, which can account for well over 50% of the total life cycle cost of these systems (Wu *et al.* 2017; Margeta 2018), and therefore has been criticised. Consequently, a new approach to prioritise pipe replacement based on both water and energy savings has been proposed (Pardo & Valdes-Abellan 2019).

The first and most direct response to climate change drivers in system rehabilitation is to include energy or GHG emission-related objectives in the rehabilitation process. The inclusion of energy considerations in UWSS rehabilitation indicates an increased awareness of the connection between water and energy in urban water systems. This is reflected in a few recent studies, where energy reduction was directly considered in urban water system rehabilitation (Saldarriaga *et al.* 2010, 2016; Roshani & Filion 2014; Pardo & Valdes-Abellan 2019), where rehabilitation strategies typically include system component replacement, refurbishment (e.g., pipe and tank lining and cleaning) or placement (e.g., valve allocation).

Some studies went a step further to calculate the GHG emissions related to energy consumption of UWSS rehabilitation (Eckelman *et al.* 2014; Hendrickson & Horvath 2014; Roshani & Filion 2015; Santana *et al.* 2019). In these studies, GHG emissions from energy consumption associated with construction (or refurbishment) of system components (e.g., capital energy consumption), system operation after rehabilitation and decommissioning of old system components were considered as evaluation criteria, indicating an increased awareness of the impact of energy consumption and the resulting GHG emissions on climate change.

However, in the majority of these studies, rehabilitation strategies were developed to minimise both water and energy consumption of the operation of the distribution system only. Embodied energy involved in system rehabilitation, although contributing to significant amounts of total GHG emissions during the life cycle of a UWSS (Wu *et al.* 2010b, 2012b), was only considered in a few studies, typically using the LCA approach (Eckelman *et al.* 2014; Hendrickson & Horvath 2014). Energy required for decommissioning old system components was only considered in one of the studies reviewed (Eckelman *et al.* 2014). This is mainly because, although energy consumption of UWSSs varies from city to city (Kenway *et al.* 2008), the majority of energy consumption in UWSSs in many cities is due to system operation related to pumping (Wu *et al.* 2012b). For example, pumping consumed 1,687,960 GJ out of the total 2,942,929 GJ (or 57%) total energy required for supplying water in Sydney, Australia in the year 2006–2007; and this figure is increased to 75% for Adelaide, Australia (Kenway *et al.* 2008).

Considering renewable energy sources

The use of renewable energy sources to replace conventional electricity generated from burning fossil fuels has become increasingly popular as a system rehabilitation objective due to the increased awareness of climate change, as well as technological advancements, which have made these technologies more accessible. Although some studies have investigated the use of various renewable energy sources, such as wind and solar, in UWSS rehabilitation (Bundschuh *et al.* 2010), solar energy is still the most popular form of renewable energy used in UWSSs (Sontake & Kalamkar 2016). It has become a popular practice to retrofit UWSS with photovoltaic pumps to reduce GHG emissions from pumping during the rehabilitation of both treatment (Taha *et al.* 2017) and distribution (Shao *et al.* 2018) systems. In a study by Taha *et al.* (2017), the authors examined the energy consumption of three wastewater treatment plants (WWTPs) with various treatment technologies in Palestine and the potential to use photovoltaic pumps for conventional energy consumption reduction. It was found that photovoltaic pumps can supply between 1 and 15% of the energy demand of WWTPs depending on the treatment technologies used, with payback periods for the initial investment of up to 19 years. A photovoltaic pumping system was also proposed as part of a rehabilitation plan for Xianmen city in China to pump recycled wastewater from a nearby WWTP to supplement the city's demand (Shao *et al.* 2018). It was found that a photovoltaic water supply system is 30% cheaper than a traditional pumping system in terms of capital investment, and it can also cover all pumping energy required (Shao *et al.* 2018).

Energy recovery from existing systems

As mentioned above, water has long been recognised as a potential source for generating energy. However, recovering energy from the use of small-scale hydro turbines within UWSSs is a relative new concept, but has attracted increasing interest in the rehabilitation planning of aging UWSSs due to technological development and pressure from population growth. Most energy generation potential within UWSSs lies in the treatment and distribution sections of the system.

Water and wastewater treatment (especially tertiary wastewater treatment for reuse) is very energy-intensive and can account for up to 5% of electricity used in many countries (Chen & Chen 2013). The treatment process also generates a large amount of methane, accounting for 5% of global methane emissions (Zhang *et al.* 2013). Methane is the second largest anthropogenic GHG behind carbon dioxide, but with over 20 times greater global warming effect (IEA 2007). On the other hand, being the primary component of natural gas, methane is a very effective fuel, which can potentially be harvested to produce energy and reduce overall global warming potential from wastewater treatment processes (El-Fadel & Massoud 2001). The profit generated from energy recovered from methane gas can provide incentives for wastewater system rehabilitation in developing countries, where these systems are often in dire need of rehabilitation. However, this may be difficult to implement due to the limited financial ability of the responsible water utilities (Cuppens *et al.* 2013). Cuppens *et al.* (2013) presented a study on the upgrade of a WWTP in Paraguay to improve water quality for reuse, including the addition of an anaerobic pond. The methane emitted from the anaerobic pond was recovered and used to partially finance the upgrade.

Within the distribution section of UWSSs, energy can be generated in the form of hydropower. Small hydropower systems within UWSSs are becoming more popular as micro-hydro turbines, such as pump-as-turbine, become more affordable and efficient (Novara *et al.* 2017). This approach is especially effective at locations where there is a large head difference between water storages or between water storages and end-users, such as in mountainous areas (Sitzenfrei *et al.* 2018) or high-rise buildings in urban centres (Du *et al.* 2017). A pump-as-turbine-based system was included in a small Alpine UWSS in Austria (supplying water to 2,000 residents) to generate energy from excess flows during low water demand seasons. The study concluded that a significant amount of profits can be achieved for both single and interacting twin systems. A similar concept was used in a study in Brazil when rehabilitating a trunk main of a UWSS, when a pump-as-turbine was added in the system to recover energy from normal system operation with a by-pass system for pressure increase during emergencies (Meirelles *et al.* 2018). In addition, pump-as-turbine was also used in high-rise buildings to replace pressure-reducing valves for leakage reduction and excess energy recovery (Du *et al.* 2017). The authors found that a maximum power output of 110 W can be achieved with 34 m head reduction under 10 m^3/h flow (Du *et al.* 2017).

Use water storage as energy-balancing storage

It is becoming more popular to supply UWSSs with renewable energy, such as wind and solar, as mentioned previously. However, these renewable energy sources are intermittent, which cannot provide reliable 24 × 7 energy supply to UWSSs (Margeta 2018). Both wind and solar energy can be highly variable, and their peak production time may not coincide with the peak energy demand (de Jong *et al.* 2013). In addition, the two sources can also be correlated, increasing risks to reliable energy supply (Widen 2011). This problem can be amplified when a large amount of intermittent energy is used beyond UWSSs to replace conventional energy from burning fossil fuels or nuclear energy. Therefore, the use of large amounts of such intermittent renewable energy needs to be balanced with the energy system's reserves, to which hydropower in the form of water stored at high elevation provides a potential alternative balancing storage. The concept of pumped hydro energy storage is not new and can date back to the 1900s (Rehman *et al.* 2015). However, the potential of using pumped hydro in UWSSs to balance renewable energy generation has only been investigated recently, mainly due to the increased awareness of climate change, which drives the use of renewable energy sources, and increased demand from population growth (Dujardin *et al.* 2017; Meirelles *et al.* 2018). By examining the best way to integrate existing UWSSs and energy systems, it is possible to construct a hybrid system for integrated water–energy management, as opposed to current UWSSs and energy systems that are managed in isolation. How to construct such hybrid systems from existing UWSS and energy systems, however, remains a challenge for future UWSS rehabilitation.

Bringing benefits to disadvantaged communities

A direct impact of the advancement of technologies is that they become cheaper and more accessible (e.g., smaller equipment and easier to install and maintain). Therefore, more and more people are thinking of how technology development can be used to improve the water supply of disadvantaged communities who previously were priced out of these technologies. For example, an economic and small-scale device was developed to mitigate arsenic contamination problems in water sources for communities in Latin American countries that do not have access to centralised water supply (Bundschuh *et al.* 2010). These devices are easier to install and maintain, and can run on renewable energy (e.g., solar), and therefore have lower operational cost compared with traditional devices, meeting the needs of those disadvantaged communities. Alternatively, new technologies have been used to generate financial benefits from UWSSs. For example, in the study by Cuppens *et al.* (2013) discussed above, energy can be recovered from water treatment facilities to finance the upgrade of the facility itself. It is therefore possible that in the future, various upgrades to UWSSs can be carried out with achieving economic profit as an objective, which brings other environmental or social benefits (e.g., reduced overall energy consumption and emissions and creation of jobs) at the same time.

Summary of responses

In response to long-term drivers and the resulting changes to UWSSs, various responses have been proposed in system planning, design, operation and rehabilitation, as discussed above. A summary of these responses is provided in Table 2. As can be seen in the table, responses that led to energy or GHG reduction are commonly considered in all application areas of UWSSs. Incorporating energy/GHGs reduction as an objective is one of the most common responses in all four application areas, driven by all three long-term drivers, especially climate change. This response is often integrated into system planning, design and operation using a multiobjective approach, where the trade-offs between the traditional economic objective and the new energy or GHG reduction objective are explored. In system operation, the reduction of energy/GHG is often achieved via more efficient and flexible operation of the system (sometimes through a multiobjective optimisation approach), which is a direct response to technological development.

The reduction in the use of conventional energy or resulting GHG emissions can also be achieved through the use of renewable energy sources in place of conventional energy sources, which has been considered in all four

Table 2 | Summary of responses to the changes to the water–energy nexus in UWSSs due to long-term drivers

	Long-term drivers			Application areas			
Responses	**Climate change**	**Population growth**	**Technological development**	**Planning**	**Design**	**Operation**	**Rehabilitation**
1. Energy or GHG emission reduction							
1.1 Considering energy/GHGs reduction as an objective	✓	✓	✓	✓	✓	☑	✓
1.2 Use of multiobjective optimisation approach	✓	✓	✓	✓	☑	☑	
1.3 More efficient and flexible operations			✓			✓	
1.4 Considering renewable energy sources	✓	✓	✓	☑	☑	☑	✓
1.5 Recovering energy from existing systems		✓	✓			✓	✓
2. Integrated modelling and planning							
2.1 Considering design and operation together	✓	✓	✓		✓	☑	
2.2 Integrating urban planning with water system planning	✓	✓	✓		✓		
2.3 Integration of water and energy system planning	✓	✓	✓	✓	☑	✓	✓
2.4 Developing decentralised (with centralised) solutions	✓	✓	✓	✓	☑		
3. Improving social benefits							
3.1 Bringing benefits to disadvantaged communities		✓				✓	

Note: ✓ indicates explicit responses identified and ☑ indicates implicit responses considered.

application areas. Incorporation of renewable energy sources has become a main aim for system rehabilitation in many studies, and typically solar energy is incorporated so that future system operation will rely less on conventional energy sources and generate fewer GHG emissions. In addition, energy recovery from existing systems is an alternative way to reduce total energy consumption and the resulting emissions. This response has mainly been driven by population growth and technological development, which made it technically feasible. Energy recovery is typically considered in both system operation and rehabilitation studies.

Another commonly proposed response to the three drivers is the use of an integrated approach for urban water system management, typically through integrated modelling. This can be conducted on a small (or cluster) scale, where the design and operation of a single water supply system are considered jointly during the system design phase, so that the life cycle cost and energy (or emissions) can be taken into consideration at the initial stage of system design. Integrated modelling can also be applied to an extended scale, where water and energy system planning is integrated into the planning of urban areas, leading to multiple benefits, such as better management of waste, energy recovery, reduced landfill and reduced GHG emissions.

The integration of water and energy systems has been considered in all four application areas as a direct response to all three drivers. It has been widely recognised that overall system efficiency can be improved through integrated planning of water and energy systems, in response to the tighter coupling between water and energy as the changes induced by the long-term drivers take effect. The consideration of renewable energy sources, such as wind and solar, increases the variability of power supply for water systems, which need to be balanced with large energy reserves. The potential of using hydropower storage in water storages (e.g., reservoirs and water tanks in high-rise buildings) as a balancing energy storage has been explored, primarily for existing systems through system rehabilitation.

Finally, advances in technologies make new technologies not only more feasible, but also more accessible (economically and physically) to communities who could not afford them previously. A few studies on system rehabilitation have explored this opportunity to improve water supply to disadvantaged communities, including the development of small-scale solar-powered devices for mitigating arsenic contamination problems in water sources for off-grid communities in Latin American countries and the use of energy recovered from water system upgrade to fund the upgrades themselves. However, this response is yet to be included as a main focus in other application areas.

CONCLUSIONS AND FUTURE DIRECTIONS

We provide a review of how the water–energy nexus within UWSSs has changed due to the primary long-term drivers of climate change, population growth and technological development, as well as the responses to this change in the nexus that have been presented in the literature on the planning, design, operation and rehabilitation of UWSSs. The traditional water–energy nexus in UWSSs is represented in Figure 1, as discussed previously; and the changed nexus due to the long-term drivers is represented in Figure 7. By comparing the two figures, it can be seen that the long-term drivers have led to changes in both the physical UWSS and the attributes of the system, and in turn the inherent water–energy nexus within the system. The drivers have led to the consideration of alternative water sources and renewable energy sources in urban water supply. This has increased the physical complexity of the system due to additional system components and the different scales of the systems involved, e.g. centralised desalination plant and decentralised rainwater-harvesting systems. The development of decentralised systems is also assisted by technological development, which has made many of the technologies more feasible on a smaller scale and more

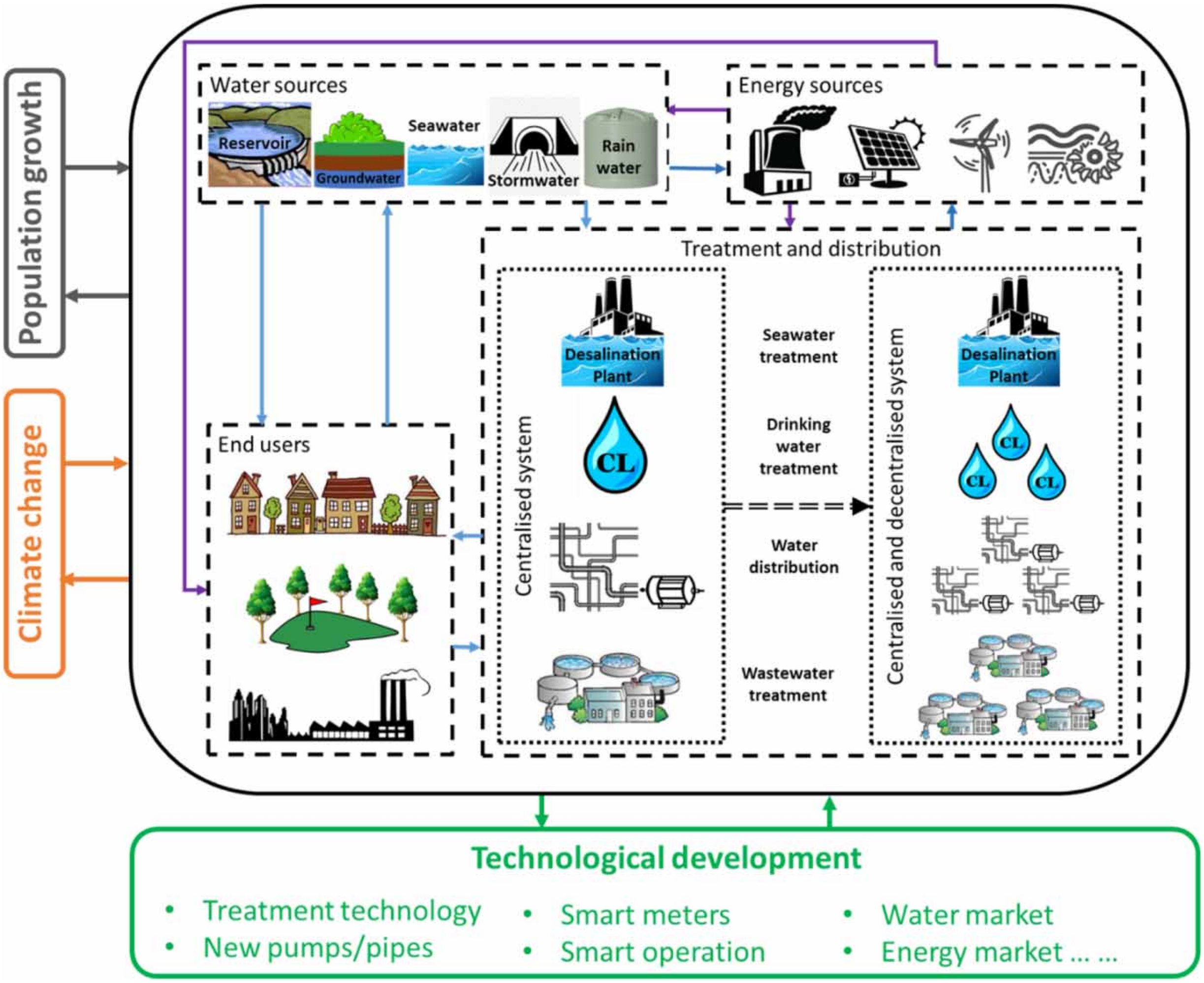


Figure 7 | Changed water–energy nexus in UWSSs due to long-term drivers. (Note: Purple arrows show the flow of energy and blue arrows show the flow of water.)

accessible to individual users (e.g., rooftop rainwater collection systems and solar panels). The consideration of alternative water and energy sources has also changed attributes of UWSSs. For example, consideration of renewable energy sources has resulted in changing GHG emissions, as well as the variability of energy supply and costs, due to the intermittency of renewable energy sources, such as solar and wind. Consideration of alternative water sources has led to the availability of water with different quality and costs. A market mechanism can be used to better manage the changing attributes of water and energy supply (e.g., via time-varying tariff or trading), which in turn will amplify the variability in energy and water prices. As a result of the changed prices, quality and availability of water and energy, end-users may change their behaviour to optimise their overall economic efficiency, for example turning on washing machines during daytime when solar energy is available, or during times when electricity prices are low. This will change the overall demand and demand pattern for water, further increasing the complexity of the entire system.

In response to the increased complexity of UWSSs and the changes in the water–energy nexus, a large number of studies have been dedicated to improving system efficiency, considering the impact of long-term drivers. Based on the review of 52 papers, we examined the responses to the changing nature of the water–energy nexus in four application areas of UWSSs, namely long-term planning, system design, system operation and system rehabilitation. The most direct response is to reduce energy consumption or related GHG emissions from both initial system construction (i.e. embodied energy/emissions) and long-term system operation. This response has been considered in all four application areas, which can be achieved via the use of a multiobjective approach, operation control, the use of renewable energy sources or energy recovery within the system. Another common response is the adoption of a more holistic approach with the assistance of integrated modelling and planning, so that the efficiency of the entire system can be improved over its lifetime. In addition, the improved accessibility of technologies due to technological development results in emerging opportunities in improving water supply to disadvantaged communities, which had been priced out of such technologies previously.

There are emerging opportunities to further improve the efficiency of UWSSs via responses to the changing water–energy–nexus due to climate change, population growth and technological development. Although energy and related emission reduction have been a main focus of responses in all application areas in the reviewed literature, most of the studies focussed on operational energy, while energy consumption due to the initial construction of the system (including manufacturing, transport and installation of system components) is only considered in very limited studies. However, embodied energy can represent a large proportion of the total energy consumed in UWSSs and be accounted for using LCA-based approaches.

Integrated modelling is a common response considered in all application areas; however, integrated modelling of combined centralised and decentralised systems and the optimisation of their integration has only been considered in a limited number of studies (Wu *et al.* 2017). For example, water-sensitive urban design, such as an integrated approach considering both centralised (e.g., stormwater harvesting) and decentralised alternative water supply sources (e.g., rooftop rainwater), has mainly been considered in the context of city planning (Brodnik & Brown 2018) and has received less attention from UWSS designers and managers (Sharma *et al.* 2016). In addition, the integrated consideration of UWSSs and energy systems in urban area planning presents promising opportunities for improving overall system efficiency and should be investigated further in the future. One tool that can be used for this purpose is urban metabolism modelling, which applies an integrated and interdisciplinary approach to account for all material (including water) and energy flows in urban systems (Dijst *et al.* 2018). However, research on this topic is still largely limited to the urban planning field (Perrotti 2019). Consequently, the general applicability of a totally integrated modelling approach of all material flows and their overall performance over different UWSSs needs to be further investigated.

Although technological development is the primary driver of many responses and has been considered in all four application areas of UWSSs, the scope of technological development considered in the current literature is quite limited. Almost all of the responses linked to technological development are due to the advancements in renewable energy or new network components (e.g., variable speed pumps, pump-as-turbine and photovoltaic pumps) and the resulting increased accessibility (e.g., reduced prices and more portable devices) due to these technologies. In contrast, consideration of recent developments in smart meters and smart sensors has been limited in scope (e.g., using machine learning techniques to extract information from increased data collected using these sensors) (Cominola *et al.* 2019). However, the full potential of these smart technologies is yet to be explored. The insights into water usage provided by smart meters can assist end-users to be more water and energy efficient, and assist service providers to better tailor their services to users' needs, improving the overall efficiency of the system (Sønderlund *et al.* 2014). The reduced cost of smart sensors allows them to be used in large numbers to cover large areas of UWSSs, for applications such as leak detection (Gong *et al.* 2018) and water quality monitoring (PUBS 2016). The recent development in IoTs has also made the use of these smart meters more convenient (Alvisi *et al.* 2019). How to use these smart technologies to improve water and energy efficiency of UWSSs by better responding to the changing water–energy nexus remains a research challenge.

In addition, how developments in policy and governance can be used to respond to the changing water–energy nexus in UWSSs is yet to be investigated. Government policies will have an impact on the development of water and energy markets, which can have a significant impact on how UWSSs should be designed and operated. Market mechanisms allow the prices of water and energy to vary over time, which will increase the complexity of decision-making for end-users, as well as system operators and water authorities. These varying prices will also change users' behaviour in terms of when to use water and energy and by how much, or result in the use of alternative supplies (e.g., roof top solar panels and rainwater tanks), increasing the complexity of system operation. System operation can be complicated further by allowing the water in the system and energy generated from UWSSs to be traded in a market. Integrated modelling considering not only the physical connections between the water and energy systems, but the dynamics introduced by human decisions are key in fully tapping into the benefits of the enhanced water–energy nexus to improve system efficiency in the future.

Furthermore, most UWSS models do not account for uncertainties associated with water demand and renewable energy supply, with the exception of limited studies on small off-grid systems (Guidici *et al.* 2019). These uncertainties are often the results of short-term climate uncertainties due to the chaotic nature of the atmosphere (Lorenz 1963), but can also come from social and political uncertainties (Maier *et al.* 2016). The short-term uncertainties related to the natural systems are often dealt with using ensemble forecasts in other environmental engineering-related fields, such as climate or flood forecasts (Wu *et al.* 2020). However, there have been limited studies on the use of ensemble forecasts to account for short-term uncertainties related to natural variability in UWSSs. The best way to develop a stochastic representation of natural uncertainties in the systems using ensemble forecasts to enable robust UWSSs to be identified in terms of both design and operation is yet to be investigated in detail. On the other hand, the impacts of social and political uncertainties on the water–energy nexus in USSSs, especially those related to uncertainty into the distant future (or deep uncertainty), are more difficult to estimate (Maier *et al.* 2016). However, deep uncertainty is particularly important for long-term planning, where decisions at the present time will have a significant impact on the social, economic and environmental wellbeing into the distant future. An adaptive approach has been found to be effective in accounting for deep uncertainty (Hamarat *et al.* 2013). The general applicability of this adaptive approach and its overall performance over the integrated design and operation of different UWSSs need to be further investigated.

This paper focuses on the water supply side of urban water systems, with wastewater systems being considered only when they are linked to water supply (e.g., considering recycled wastewater). It is well known that wastewater treatment is one of the major energy consumers in urban water systems, and the water–energy nexus in wastewater treatment systems has been well studied (Xu *et al.* 2017; Maktabifard *et al.* 2018). As treatment technologies develop, significant energy savings can be achieved in wastewater treatment and recycling; and significant energy recovery can be achieved from sludge management (Maktabifard *et al.* 2018). However, challenges lie ahead in developing a comprehensive model to represent integrated water–energy systems in an urban context to optimally manage not only UWSSs, but urban areas with all of their components integrated as a whole, and how to represent uncertainties, both short-term and long-term, in these models.

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