Imperial College London

Grantham Institute
Briefing paper No 32

October 2019

Climate change and the human-made water cycle: Implications for the UK water sector

CHARLES ZOGHEIB[1] AND NIKOLAOS VOULVOULIS[2]

Headlines

- Climate change is already happening, and the UK's climate will continue to change as a result of greenhouse gas emissions, with the long-term resilience of its infrastructure at risk.
- The water sector cannot adapt to the challenges of climate change in isolation, as policy effects in one sector will have indirect effects in others.
- Current demand pressures and reductions in abstraction licences – rights to draw water – are causing supply-demand deficits and this is coupled to the impacts of climate change. If no action is taken, the current high standards of service that is offered at a fair price, and without causing environmental damage, could soon be at risk.
- While impact on water flows might not yet be measurable, there is evidence to show that if water companies carry on with 'business as usual', we risk a future without enough water for people, business, farmers, wildlife and the environment.
- With water as the key medium that links atmospheric temperature rises to changes in human and physical systems, government, water companies and all the players in the wider sector need to play a more proactive role in accelerating the transition to a circular economy, while helping people, politicians and decision makers to understand and prepare for the risks of climate change.

Executive Summary

Climate change will affect all sectors of the economy, and its impacts could jeopardise water, food and energy security. Hydrological responses to climate and land use changes are expected to cause a wide range of environmental impacts, and water is the primary medium through which we experience the effects of climate change. Available projections indicate high variability in such effects, mainly in the risk of shortages in environmental and public water supplies, in addition to negative effects on water quality through, amongst others, flooding and saline intrusion.

1 Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK
2 Centre for Environmental Policy, Imperial College London, London SW7 2AZ, UK

Contents

Executive Summary 1
The UK water sector and its regulatory context.................................... 2
UK climate change and water sector impacts 4
The challenge of addressing climate change and sustainability 5
The water-energy-food nexus and the circular economy....................................... 7
Recommendations 10
Conclusions 10
References 10
Acknowledgements 12
About the authors 12

Grantham Briefings analyse climate change and environmental research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other publications are available from **www.imperial.ac.uk/grantham/publications**

The impact of wetter winters and drier summers on water resources, water quality and biodiversity predicted for the UK, together with changes in water demand over the next 25 years, could see climate change as the biggest risk to the water sector and, as a result, to the UK economy.

While climate change mitigation is a key challenge for water companies, as large consumers of energy, adaptation options, other than demand reduction, have received less attention. While water companies are increasingly mindful of the risk climate change will pose and are actively considering it alongside other business risks, they are being challenged to improve their performance, with significant further work required to balance the needs of the environment with those of population, development and agriculture.

To respond to these challenges, there is a need for a comprehensive and systematic understanding of the water sector's dependencies and interconnections across the whole economy, particularly the interactions between water, food and energy. Wider collaboration and coordination are required, and this means expanding beyond traditional 'integrated water resources management', reaching out and contributing to larger agendas including disaster risk management, sustainable landscapes, resilient cities, climate-smart agriculture and sustainable development. Water is the great connector across these agendas – in many ways water is to adaptation what energy is to mitigation. The water-related risks posed by climate change have severe consequences for all sectors in the economy, and water companies, while already looking into solutions for the challenges ahead, can play a key role in preparing society for these risks. Decoupling economic growth from natural resources and pollution, as the UK economy needs to become more circular, also means that water companies can play a leading role in the transition to the circular economy, which in turn offers new ways of looking at these challenges. For example, so-called 'closing the loop' – recycling water for potable and non-potable uses on top of reducing household water demand and water supply pipe leaks – offers creative approaches to demand management along with new capacity. Such an approach could allow UK water companies to make a positive contribution to addressing the many social and environmental challenges we face, while delivering a key public service with benefits to customers, their shareholders and the environment.

Introduction

Climate change is manifesting itself in a multitude of ways. As of 2012, average surface temperatures across the Earth have risen by approximately 1.15°C since the onset of the Industrial Revolution[1]. Under baseline scenarios, where no effective steps are taken to reduce greenhouse gas emissions significantly, warming is projected to reach around 4.5°C by the end of the century[2]. On the mitigation front, the Paris Agreement, accepted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), aims to hold this increase to well-below 2°C, a level beyond which significant and irreversible impacts on both natural and socio-economic systems would occur[3]. In order to meet this goal, major decarbonisation efforts are required. In parallel to these efforts, adaptation to the inevitable impacts of climate change requires a cross-sectoral and cross-disciplinary approach to deal with both short-term operational risks as well as longer-term planning and provision issues[4].

Among the most serious impacts of climate change are the potential changes in the Earth's water cycle[5]. As climate change warms the atmosphere, altering the hydrologic cycle, changes to the amount, timing, form, and intensity of precipitation will continue. Other expected changes include the flow of water in catchments, as well as the quality of aquatic and marine environments. These impacts are likely to affect the programmes designed to protect water quality and public health. While the water sector already deals with such risks as a fundamental part of their business, in a fast-changing climate their existing systems and practices may not be adequate.

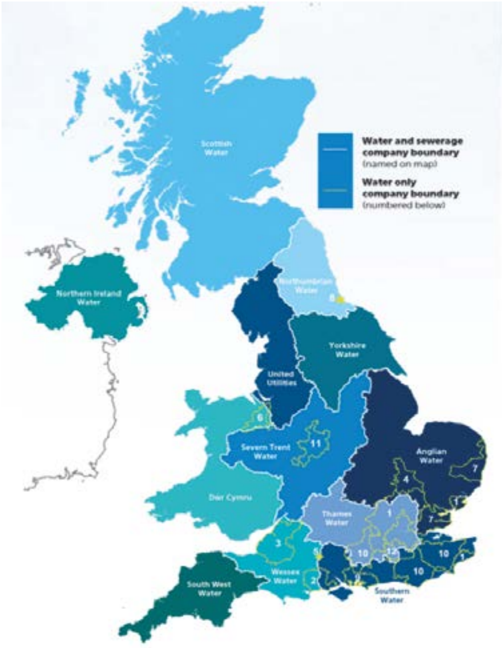
In this briefing paper, we approach the challenges of climate change that the water sector will face from a systems perspective. We start by considering the key institutional and regulatory settings of UK water supply and wastewater treatment operations, then reviewing the expected impacts of climate change in the UK, before we look at the challenges and opportunities for the water sector. Greater resource coordination, management and policy convergence across water, energy and food systems, the so-called WEF nexus, as well as more fundamental shifts to paradigms compatible to climate change, such as a transition to a circular economy, are discussed. We explore the role of the water sector in such shifts and conclude with policy recommendations.

The UK water sector and its regulatory context

The UK has a total of 350,000 km of water mains and 625,000 km of sewers[6]. Moreover, a major part of both networks built in the 17th and 19th centuries respectively is still in use today[7]. In England and Wales, the water industry was privatised in 1989. Today there are ten large regional, independently-run companies and organisations that provide drainage and sewerage services, each over a wide area, and supply water to most customers in their areas of operation, as well as some 'water-only' companies. Scottish Water is the single publicly owned water and wastewater company that supplies water and sewerage services to the whole of Scotland and is accountable to the Scottish Executive. Northern Ireland services remain in the public sector — the Water Service is an executive agency within the Department for Regional Development (Figure 1).

The Department for Environment, Food & Rural Affairs (Defra) and the Welsh government set the policy and regulatory framework for the water industry in England and

Wales[8]. The Water Services Regulation Authority (Ofwat) is the independent economic regulator of the water industry. Its main statutory duties include protecting the interests of consumers, securing the long-term resilience of water supply and wastewater systems, and ensuring that companies carry out their functions and are able to finance them[9].



Water UK

We bring people together to create better policies for the future of water

Water only Companies
(see below for water and wastewater companies and other local suppliers that cannot be shown on this size of map)

1. Affinity Water
2. Bournemouth Water
3. Bristol Water
4. Cambridge Water (South Staffs)
5. Cholderton and District Water
6. Dee Valley Water
7. Essex & Suffolk Water (Northumbrian)
8. Hartlepool Water (Anglian)
9. Portsmouth Water
10. South East Water
11. South Staffs Water
12. Sutton and East Surrey Water

Figure 1: The UK water industry

Water companies interact with a number of stakeholders and interest groups (figure 2), and must also comply with European and national drinking water and environmental regulations, implemented by Defra, the Welsh government, the Environment Agency and Natural Resources Wales. The Environment Agency, the Drinking Water Inspectorate and Natural Resources Wales monitor companies' compliance and advise them on the actions required to comply. Ofwat limits the prices water companies can charge, by setting price limits for fixed five-year periods where companies submit what is termed an asset management plan (AMP). To that effect, Ofwat has carried out five price reviews since privatisation. The most recent concluded in December 2014, setting water and sewerage price limits from April 2015 to March 2020.

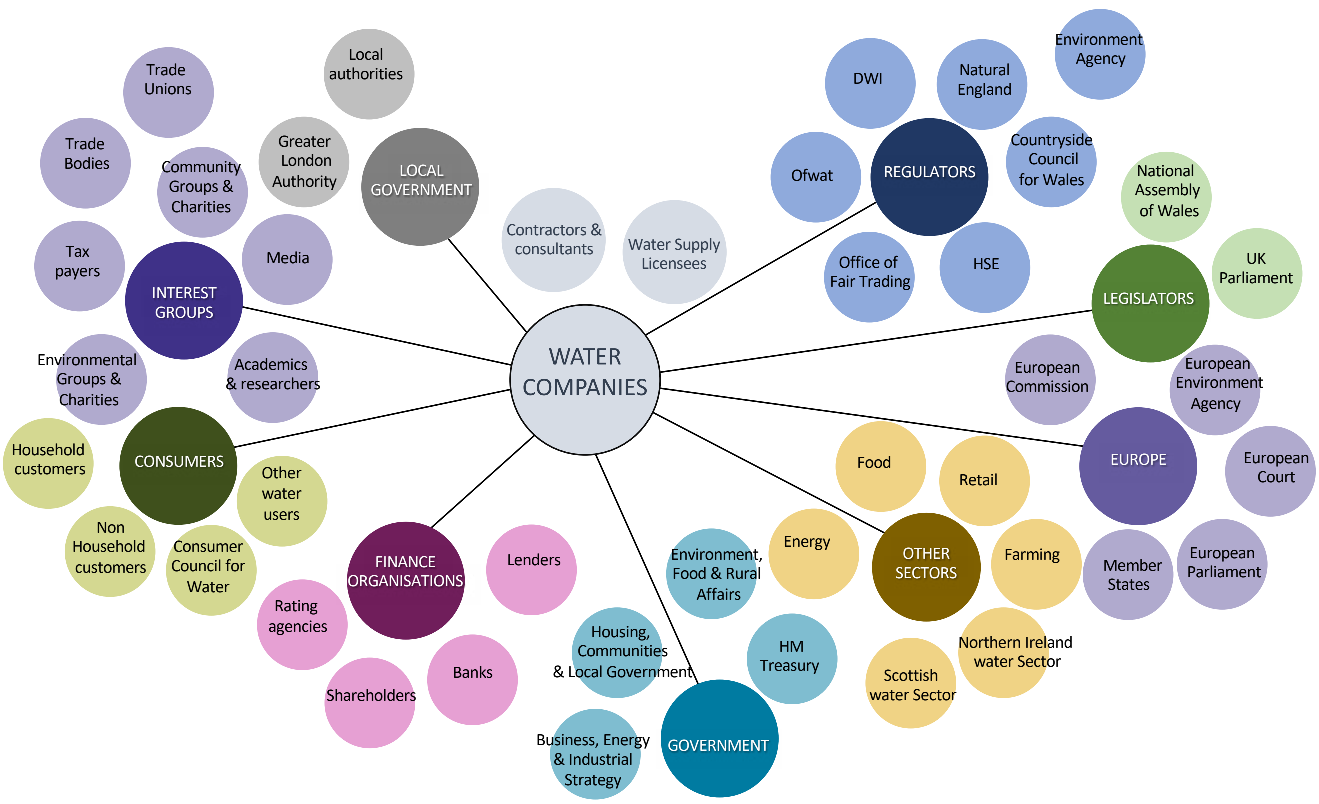


Figure 2: The UK water sector: water companies, regulators, interest groups and other stakeholders

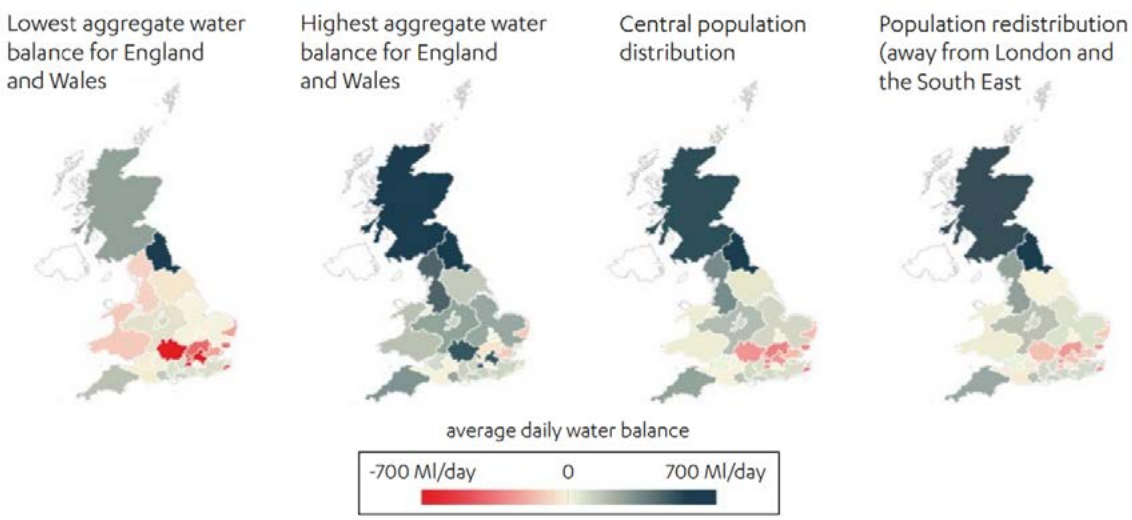
Recognising that there were significant benefits to solving some environmental challenges multilaterally, the European Union (EU) was given legal authority to legislate in this area by member states. A series of single issue Directives, then increasingly replaced by 'Framework' and 'Daughter' Directives (e.g. the Water Framework Directive and the Waste Framework Directive), led to a more integrated approach to environmental protection[10]. EU Directives have been a major driver for investments in the water sector, and have driven consistency and common standards across the EU[11].

In light of the UK's expected exit from the EU and the publication of the 25 Year Environment Plan (25YEP), several changes to environmental regulation are needed to implement the Plan's general policy intents. A substantial amount of goals explicitly recognise the interdependencies between water, food and energy, with flooding and land use being an example. As water sector players are largely UK-based (although often foreign-owned), and there is no international trade in water itself, Brexit has proved to be a relative sideshow compared to other sectors. However, concerns about funding for infrastructure, investment in research, and environmental regulations related to Brexit are adding to the 'uncertainty' about the sector's preparedness to the challenges of climate change[12].

UK climate change and water sector impacts

Nine of the ten warmest years for the UK have occurred since 2002 and all the top-ten warmest years have occurred since 1990[13]. In the recent past (1981-2000) the chance of seeing a summer as hot as 2018 was low (less than ten per cent)[14]. The chance has already increased as a result of climate change and is now approximately between ten and 20 per cent, and projected to increase further[15]. There has also been a slight increase in annual average rainfall over the UK in the last few decades, but with a very dry summer in 2018[15]. An increase in annual average rainfall is particularly marked over Scotland where the most recent decade (2008-2017) has been on average four per cent wetter than 1981 – 2010[14]. At the seasonal scale, UK summers for the most recent decade (2008-2017) have been on average 17 per cent wetter than 1981-2010 and 20 per cent wetter than 1961-1990, with only summer 2013 drier than average[13]. The summer of 2018, however, was the driest since 2003. More details can be found in the Met Office's latest annual State of the UK climate report, published in the International Journal of Climatology in July 2019.

According to the 2019 Committee on Climate Change Report to Parliament on Progress in preparing for climate change, vulnerability and exposure to climate change are increasing across a range of priority areas, including terrestrial and freshwater habitats, development in flood risk areas, and potential supply change interruptions for products and services related to water. In general, climate change is expected to exert an impact on the UK water sector through the coming decades mainly by altering groundwater and surface water availability and seasonality[16]. Longer and hotter summers will raise maintenance and running costs as well as energy consumption due to water treatment plants needing to run at peak flow rates for longer, while increased flooding is expected to increase asset vulnerability to climate change. The total area of impermeable surfaces in urban locations has increased by 30 per cent between 2001 and 2018[15]. As a proportion of total urban area, which has itself increased, this equates to a 22 per cent increase in impermeable surfaces between 2001 and 2018 in the UK. Furthermore, urban greenspace, which has a host of



Footnote: Average daily water balance is calculated based on the annual difference between deployable output and distribution input. Further details on the Commission's modelling are available on the Commission's website.

Figure 3: Water balance (million litres per day) for water companies across the UK in 2050. Reproduced with permission from the National Infrastructure Commission (2017)[19]

benefits for reducing flood and heat risks, continues to decline, from 63 per cent of urban area in 2001 to 55 per cent in 2018[15].

The condition of terrestrial and freshwater habitats is not improving quickly enough to meet Government targets. There are still substantial gaps in our understanding of: how businesses are affected by extreme weather and the actions they are taking to prepare for climate change, trends in vulnerability and exposure to surface-water flooding and coastal erosion, the resilience of infrastructure services and infrastructure interdependencies. While the water sector continues to make detailed plans for dealing with a range of future water availability scenarios, as it has done for over 20 years, more can and needs to be done to reduce consumption and leakage further and faster in order to manage the risks from reduced water availability in the future.

Risks from reduced water availability, pollution and higher water temperatures will also increase the degradation of freshwater habitats and compromise the viability of some freshwater species. Water scarcity is also an urgent risk to people, businesses, infrastructure, agriculture and wildlife, as the majority of catchments in England are projected to have insufficient water to meet demand by 2050[17]. As the UK population is also projected to increase by 20 per cent to around 77.5 million by then, the effects of climate change mitigation and adaptation will interact with population and demographic shifts, economic changes, and land use changes, adding to the complexity of the challenge.

As the climate changes, the magnitude and variability in space and time of the hydrological cycle are expected to increase together with storm and drought durations and frequencies across the globe[2]. However, predicting the magnitude and direction of change of key variables such as precipitation, and surface and groundwater availability is more challenging and uncertain[2,18].

While we have not yet experienced water flows being affected in most of the UK, and despite the uncertainty associated with climate change impacts, there is enough evidence to warn us of a future without enough water for people, business, farmers, wildlife and the environment. Current demand pressures and reductions in abstraction licences, are already causing supply-demand deficits and are expected to become widespread beyond Southeast England in the 2050s, as reflected by an increasingly negative daily water balance (figure 3). Moreover, with high population growth, high carbon emissions and little update to current infrastructure, demand for water could increase by four to 18 per cent, leading to a six to 11 per cent reduction in available water. In the case of no action, Northwest England is also at risk of such reductions in availability due to overreliance on surface water sources.

The challenge of addressing climate change and sustainability

Notwithstanding the successes achieved in the delivery of water and sewerage services since privatisation, the water sector is currently facing calls to address sustainability and adapt to the challenges of climate change[20]. For example, the growing risk of drought in England and Wales is considered to be more significant than previously thought, with drier areas of the country (the south and east of England) facing a higher risk of more severe droughts than those experienced in the past, while English regions further to the north and west are also more exposed to the prospect of future water shortages[21]. In the longer term the indications are that climate change could mean greater variability in the raw water supplies available, but both the supply-side large infrastructure projects up for consideration as well as the demand-side water usage reduction measures considered, fall short of breaching the availability-demand gap, due to high investment costs and the unresponsive public respectively. The leaks from aging water mains, issues of inadequate water pricing and metering and patchy supplier and regulatory support for water efficiency measures often come second to big infrastructure projects promising a more secure investment return. These in turn often seem to suffer from short-sightedness and lack of overall strategy[22–24], shortcomings in the ability to understand and handle risk[21], and ending up having a lower chance becoming a reality. On the other hand, with any large investment, companies must prove to relevant stakeholders and investors that there is a strong business case to justify that spend. But climate change is a very complex issue, often requiring significant investment and where pay-back may not be seen for five or more years[25].

Infrastructural deficits could hinder adaptation efforts to climate change. It is recognised that, as well as investments in new infrastructure, existing assets will also need major repair and maintenance as the risks of leaks, bursts and breakdowns increase. To this end, it is expected that £96 billion will be required in additional investment by 2030 in order to merely maintain the status quo, let alone adequately adapt to climate change[26]. For instance, leakage constitutes a significant challenge in many water supply networks across the UK. It accounts for ten to 20 per cent of total water distribution input[27]. Leakage costs have been historically viewed solely as a direct cost on the water companies without consideration of the broader systemic environmental and social implications[17]. Leakage is both a major source of water loss in quantifiable terms and a waste in energy input during the treatment process. Furthermore, service affordability suffers as consumer demand is met with higher costs as more water is drawn to compensate for these losses. Currently, most companies use the 'economic level of leakage' concept, which involves reducing leaks up to a level at which the 'marginal cost of reducing leakage is equal to the benefit gained from further marginal leakage reductions'[18].

In other words, leakage is reduced to the point where it becomes more expensive to further reduce it than simply compensating by adding extra water supply into the network. Ofwat has proposed the concept of 'sustainable economic level of leakage' in order to remedy this[28].

Water companies have also started to invest in so-called 'soft' measures; even though progress to date has been slow. For instance, water metering has been poorly implemented even though studies have shown that it can potentially reduce demand by up to 15 per cent in addition to enabling immediate and more accurate identification of leakages via real-time pressure change detection[29]. In one case in Queensland, Australia, rapid identification of leaks via smart meters was found to contribute to a reduction of five to ten per cent in consumption throughout the city[26].

Failing to act on a long-term perspective and implement programmes consistent with sustainability could therefore result in water shortages; degradation of water quality; climate change-induced challenges, such as rising sea levels and changed precipitation patterns; and associated economic, health, social, and ecosystem impacts. Managed efficiently, water plays a vital role in strengthening the resilience of social, economic and environmental systems in the face of rapid and unpredictable changes.

Water is fundamental to sustainable development, affecting social needs, economic development and environmental limits. The UN 2030 Development Agenda and the 17 Sustainable Development Goals (SDGs) recognise that water is embedded in all forms of development – food security, health, and poverty reduction, in sustaining economic growth in agriculture, industry and energy generation, and in maintaining healthy ecosystems. Indeed, SDG 6 'Ensure availability and sustainable management of water and sanitation' reflects that future social development and economic prosperity depend on sustainable management of freshwater resources and ecosystems. As the SDGs apply to all UN member states, the UK itself will be expected to progress towards SDG 6 targets relating to water resource management and improvements in sanitation for the protection of the ecology of freshwater rivers and lakes. The ultimate goal will be the delivery of a sustainable integrated water cycle (figure 4), in which we are able to meet our needs for water and sewerage services while also enabling future generations to meet their needs. This requires viewing the services provided by the sector from a circular perspective. Rather than focusing solely on treatment, we should prevent contamination or create a system in which water retains full value, and circulates in closed loops, allowing repeated use.

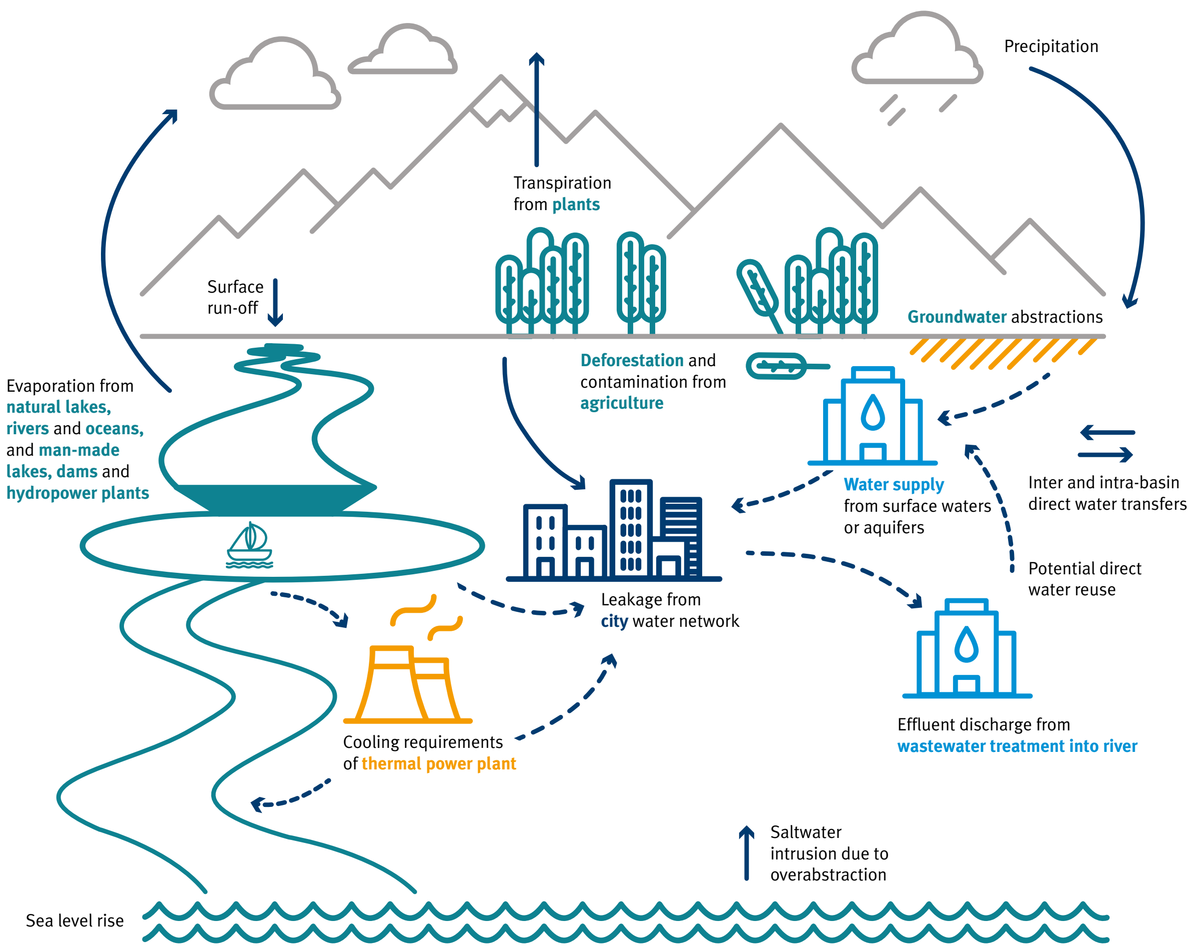


Figure 4: The human-made water cycle as an integrated complex system

The water-energy-food nexus and the circular economy

Despite the many interactions between water, energy and food systems, most frequently their management currently takes place in silos with limited attention given to their interdependancies[30]. For instance, food and land use is not mentioned in the 2013 UK Energy Act (only water is mentioned but in a narrow legal context), whereas the UK Water Act 2014 makes no mention of either energy nor land use[31]. Similarly, the recently published second UK National Adaptation Programme[32] did not consider several factors that are key to adaptation in the water sector. For instance, hard infrastructure projects typically only have lifespans of several decades due to a lack of modularity and the high costs involved[33].

While there are various tools to cope with the large number of potential future scenarios and design projects that have sufficient in-built or potential flexibility (such as Robust Decision-Making, Real-In Options, Dynamic Adaptive Pathways[34–37]) to facilitate decision making that is resilient to as many futures as possible, these tend to provide solutions that are not the most cost-effective nor always politically feasible[38] from a sectoral perspective. Moreover, such approaches often inadvertently fail to consider wider socio-economic and ecological impacts. For example, the use of nature-based solutions (NBS) within urban areas are increasingly being considered not only for supporting biodiversity conservation but also generating additional environmental, economic, and social benefits, and fostering the functioning of ecosystems as essential backbones to climate change mitigation and adaptation. However, they find little application with sectoral decision making[39]. NBS face a broad range of potential barriers in their implementation and up-scaling as tools for climate change mitigation and adaptation. This is caused by the disconnect between short-term actions and long-term goals, the discontinuity between short-term actions and long-term plans, sectoral silos, and a lack of systemic thinking.

It is increasingly clear that effective and sustainable solutions to the challenge of climate change will require greater understanding and consideration of the linkages and inter-dependencies between sectors such as water, energy and food[40]. These systems interact with each other and the environment, and the water-energy-food (WEF) nexus is the interrelated complex system where energy, water, food and material flows/waste treatment systems intersect. The emergence of the WEF nexus has resulted in changes to the way we perceive our natural resources. Stressors such as climate change and resource scarcity have highlighted the fragility of our WEF systems, necessitating integrated solutions across multiple scales. Delivering these solutions will require moving from a sectoral approach towards a holistic approach, that captures the interconnections between food, energy, health, trade, the environment and water. A systems framework could facilitate such an approach, allowing water companies to build relationships and benefit from synergies in the wider system. Detecting emergent properties and impacts, reconciling conflicting interests, and evaluating trade-offs from the interaction of various systems, requires a quantifiable well-defined systems framework[44].

In 2017, Ofwat called for the water companies to adopt a systems thinking mind-set at all levels of their businesses as part of their resilience business planning for the upcoming 2020-25 Asset Management Plan (AMP) investment programme[41]. According to Ofwat, this is necessary for water companies to respond to the resilience challenge and will embed corporate, financial and operational resilience, into their long-term business planning and processes. The need to adopt a systems approach at all levels of their businesses will be vital for water companies to have a better understanding of the interrelationships and interdependencies across the systems underpinning their service delivery. These include macro systems: the broader natural environment; social systems; the economy and agriculture, which operate in association with infrastructure systems such as communications; energy networks; and highways drainage.

The water industry has already started applying systems thinking, for example to ensure it can respond quickly to incidents and ensure the public retain confidence in its service, with many potential applications still to be explored[42]. The recycling of biosolids following anaerobic digestion of sewage sludge (the main by-product created in the treatment of wastewater) is a widespread practice and a good example of the application of such an approach (figure 5). The biogas produced is a source of renewable energy, the recovery of nutrients and use of biosolids from the process on land as fertilisers is a well-established practice. However, technological developments and breakthroughs in this area could deliver further benefits. For example, co-digestion with food waste offers opportunities for environmental and commercial benefits and using surplus heat from the process can also offer added value. Looking beyond the boundaries of a single facility to develop synergies and collaborations between relevant stakeholders and regulators could further unlock the potential of this approach.

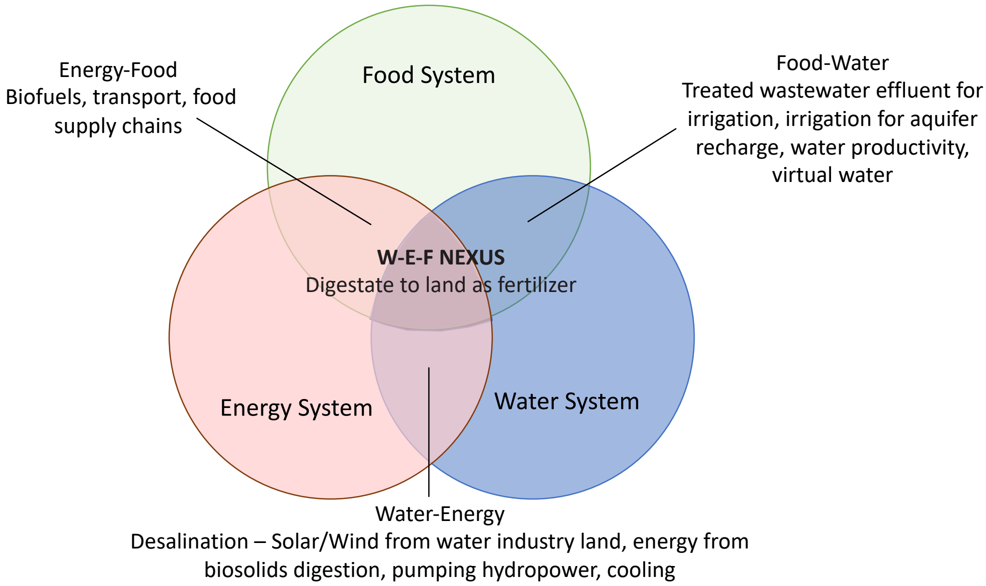


Figure 5: Anaerobic digestion of sewage sludge as an example of the food-water-energy nexus approach delivering multiple benefits

Adopting a systems nexus approach in the water sector could result in a paradigm shift from business as usual and sectoral practices towards multiple benefits, reducing trade-offs and promoting synergies[30,43]. The need for more carbon, water and resource efficiency, more innovation, adoption of water reuse, and the sustainable management of catchments, all offer new opportunities for the water sector[44,45]. Developing relationships in the industry, more integration with other sectors and research partnerships with universities can further facilitate these opportunities delivering both economic and environmental benefits[12]. For instance, a long-standing research partnership between Imperial and Anglian Water serves as a model for how fruitful collaboration between water companies and research institutions can deliver benefits ranging from new ideas and horizon scanning to development of skills, capability and profile. These kinds of rationale are closely interrelated and contribute to a model of open innovation, in which companies actively seek to benefit from knowledge and expertise from world leading academic research institutions.

At the time of writing, UK lawmakers were considering new legislation to both replace existing EU regulations, such as the Common Agricultural Policy, and implement the 25YEP. These plans are promising as they attempt to bring systems thinking into practise. The proposed Agriculture Bill, for example, shifts farmer subsidies from rewarding production towards the provision of public goods, sustainable land management and food production. The Environment Bill would create a new watchdog, the Office for Environmental Protection (OEP), to secure environmental outcomes and to aim to change planning policy towards a much more integrated and environmentally aware mind set. The 25YEP's goal of net environmental gain in development is crucial to the realisation of this core set of objectives. However, implementing these approaches will be challenging. What constitutes net environmental gain? How will negative impacts of a project be offset? For instance, if a woodland has to be replaced by an urbanised area, how will the lost carbon sequestration ability and biodiversity loss be offset, considering that a one-for-one replacement is impossible to achieve in such a scenario? Will gains in other sectors such as improved water infiltration be enough? A generalised natural capital market[46], similar to carbon emissions trading schemes currently in place, could be a way to resolve the challenge of one-to-one substitutability. In such a market, a negative environmental impact in an area could be offset by an improvement in another. Implementing such a proposal would require very detailed understanding of the natural systems that underpin the entirety of the economy, including relationships between water provision, energy and food production. Water can take a central role in this endeavour due to its very dynamic and kinetic nature. For instance, a plot of land has very different hydrological relevance in terms of flood control and water resources provision if it is located upstream or downstream of a river. In contrast, a ton of CO_2 emitted anywhere in the world has the exact same environmental effect. Other relevant questions would include the specific importance of that plot of land to the broader economy. For instance, how much food is produced and how much energy is consumed? Fitting together these various factors and quantifying those linkages would be a challenging task.

However, like businesses of every kind in every other sector, the water industry will not just face serious risks, but also compelling opportunities. Businesses are key to achieving the Sustainable Development Goals and Paris Agreement. Developing strategies with the SDGs and Paris in mind, rather than treating them as a corporate social responsibility (CSR) tick-box exercise, could unlock a wealth of opportunity. One of these is what is often referred to as the 'circular economy'; an economy's ability to grow while resource use is declining and the decoupling of economic growth from resource consumption and pollution[47]. The business case for a transition to a circular economy is compelling in terms of economic outputs, and jobs and environmental benefits. It also offers a business model that enables the economy to grow, while minimising the amount of natural resources extracted[48].

In the water sector, this is reflected by increased reuse, recycling and efficiency. For instance, alternative supply sources to deal with water shortages are becoming more attractive. Reverse osmosis desalination is receiving an increasing amount of attention[49], as desalination of seawater is an effective solution, providing a seemingly unlimited, constant supply of high-quality drinking water without impairing natural freshwater ecosystems. However, desalination plants and processes still require substantial energy inputs and chemical decontaminants in operation, in addition to carbon emissions. From a sustainability perspective, there are potential negative impacts arising from increased demand and usage[30], including issues with brine production and the need for management of the costs and impacts of the additional wastewater produced. Still, improvements underway are making it cheaper and more environmentally friendly, suggesting it will have a role to play if used sustainably. This application of the WEF nexus approach shows how systems thinking can turn barriers into opportunities. The Beckton plant (see Box 1) is located within London's largest wastewater treatment site (one of the largest in Europe), treating wastewater from over 3.5 million customers, and in need of expansion. The desalination plant could be used in the future to purify treated wastewater to the level at which it could circulate within the potable water network[51]. This is already the case in Berlin where groundwater is the main source of potable water but an annual precipitation of around 571 mm/year is is not sufficient to replenish aquifers (see Box 2).

From a circular economy perspective, water reuse is a win-win option. The full cycle of wastewater management is a critical component of the cycle from source, through distribution, collection (sewered and onsite sanitation systems) and treatment, to disposal and reuse, including water, nutrients and energy recovery[47]. A transition to a circular economy could result in the wide adoption of water reuse as an alternate water supply. The closer the system gets to direct reuse, the larger the cost savings in terms of materials, energy, labour, capital and the associated factors, such as greenhouse gas emissions, water or toxic substances. With policy changes, these innovations that combine profit making with green technologies could play a critical role, allowing the water sector to address sustainability challenges. These examples illustrate the benefits of a more participatory, integrated and holistic approach to the services offered by the water sector.

The shift to a circular water economy holds much promise. Water is the most important shared resource across all supply chains, and wastewater offers an opportunity to close the loop, extract value from sludge, and reclaim gas, chemicals and nutrients. This potential to balance resource use and reclamation places the water sector at the heart of the circular revolution. Design is a critical part of the circular economy, and new ways of thinking about how the economy operates and new business models will need to be applied to the water and wastewater industries. Appropriate legislation and changes in current regulatory regimes will be needed to make such a shift. New policies, practices and business models must be based on evidence. A better understanding of the water-energy-food nexus can provide the positive reinforcement needed to stimulate both new policies and regulatory actions. The coming years will be critical for the sector's transformation which needs to use water more efficiently, lower its carbon-based energy consumption and provide valuable materials that have a demonstrable impact on attaining the SDGs. The ultimate task will be managing the whole system as one in which water circulates in closed loops, retains its value and allows for its repeated use.

Box 1: The Beckton desalination plant

Beckton is home to the only large-scale desalination plant operating in England taking its brackish water from the Thames estuary: built at a cost of £250 million, the plant can produce 140-150 million litres of water per day, enough to provide water to a million Thames Water customers. While using about twice as much energy as a conventional water treatment plant, an energy start up – CHiP – located adjacent to the site allows for commercial revenue[50]. CHiP is selling renewable electricity generated using recycled fat and oil from London's restaurants and households that could otherwise have caused costly blockages in sewers. Furthermore, a 64m-tall 2.3MW turbine with a 70m diameter rotor turns wind into electricity, giving it equivalent capacity to power around a thousand homes (eight per cent of the energy needs of the plant).

Box 2: Water reuse in Berlin

Berliner Wasserbetriebe, the region's water and wastewater provider, supplies around 600,000 cubic meters of drinking water while treating approximately 660,000 cubic meters of wastewater each day, using it to artificially recharge aquifers through infiltration ponds and bank filtration by means of natural lakes[52]. The groundwater is then abstracted to supply 3.5 million people in Berlin with drinking water without any need for disinfection.

Recommendations

- Water companies, regulators, stakeholders and the public need to better understand the risks of climate change and take responsibility for securing long-term resilience to deal with sustainability challenges.
- The challenges of climate change are so critical to the services provided by the water sector that if consumers are to continue to receive them in the future, sustainable practices and strategies need to be put in place today.
- Coordination, collaboration and public engagement can help the sector to better define future needs in order to invest in options that allow the delivery of a sustainable water cycle.
- Through a cross-societal approach, the water sector can initiate wide economy discussions, develop collaborations and initiatives, taking a leading role in addressing climate change and kickstarting the solution with the greatest potential: the transition to a circular economy.

Conclusions

Climatic and demographic changes will lead to major stresses on global and local water resources, affecting all sectors of the economy. The UK water sector will be affected both directly, by water availability changes, and indirectly, for example with more extreme temperature fluctuations leading to higher energy consumption and higher cooling requirements. Consequently, these shifts will reduce the stability and increase the unpredictability and complexity of water systems.

Both sustainable economic development and environmental protection are needed for improved human well-being, particularly as it is now recognised that environmental degradation diminishes the capacity of the planet to sustain economic development. The emerging worldview that these two goals cannot be in conflict could fundamentally change current business models and investment strategies. For example, wastewater must no longer be seen as a problem but as a solution that can help provide sustainable infrastructure services, improve the financial viability of operators and environmental quality, and strengthen the resilience of the systems.

Action to tackle climate change cannot be taken in isolation. Collaboration on research, development and deployment of new technologies, and public engagement can accelerate the transition to a sustainability economy. A 'systems mindset' can facilitate this process and allow the water sector to take a more strategic role, preparing us for the impacts of climate change.

References

1. Atkins Global. Future Proofing the UK water sector. (2013).
2. IPCC Working Group 1, I. et al. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *IPCC* AR5, 1535 (2013).
3. Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* 534, 631–639 (2016).
4. Pachauri, R. K. *et al. Climate Change 2014 Synthesis Report. Russian Federation), Hoesung Lee (Republic of Korea) Scott B. Power (Australia) N.H. Ravindranath (India)* (IPCC, 2014).
5. NASA Earth Observatory. The Water Cycle and Climate Change. (2010). Available at: https://earthobservatory.nasa.gov/features/Water/page3.php.
6. UKWIR. *Long Term Investment in Infrastructure.* (2017).
7. Cuttill, P. *Thames Water Trunk Mains Forensic Review.* (2017).
8. Defra. *Water Bill, Organisations involved in the regulation of the water sector.* (2014).
9. National Audit Office. The economic regulation of the water sector. Hc 487, 52 (2015).
10. Craig, P. P. (Paul P. & De Búrca, G. (Gráinne). *EU law: Text, cases, and materials.* (Oxford University Press, 2015).
11. Voulvoulis, N., Arpon, K. D. & Giakoumis, T. The EU Water Framework Directive: From great expectations to problems with implementation. *Sci. Total Environ.* 575, 358–366 (2017).
12. Fernandez, R. *Collaboration Between Universities and Business in the UK.*
13. Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A. & Legg, T. State of the UK climate 2017. *Int. J. Climatol.* 38, 1–35 (2018).
14. Lowe, J. A. et al. UKCP18 Science Overview Report. *MetOffice.gov.uk* 2, 1–73 (2019).
15. Committee on Climate Change. *Progress in preparing for climate change – 2019 Report to Parliament.* (2019).
16. DEFRA. *Future water – the Government's water strategy for England.* (2008).
17. HR Wallingford. *CCRA2: Updated projections for water availability for the UK.* (2015).
18. Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438, 303–309 (2005).
19. Commission, N. I. Congestion, capacity, carbon: *Priorities for national infrastructure.* (2017).
20. Bevan, J. Climate change: too true to be good. *Environment Agency* (2018). Available at: https://www.gov.uk/government/news/speech-climate-change-too-true-to-be-good.

21. Water UK. *Water resources long term planning framework.* (2016).

22. Nazemi, A. & Wheater, H. S. On inclusion of water resource management in Earth system models – Part 2: Representation of water supply and allocation and opportunities for improved modeling. *Hydrol. Earth Syst. Sci* 19, 63–90 (2015).

23. Nazemi, A. & Wheater, H. S. On inclusion of water resource management in Earth system models -Part 1: Problem definition and representation of water demand. *Hydrol. Earth Syst. Sci.* 19, 33–61 (2015).

24. Gleick, P. H. *et al.* Improving Understanding of the Global Hydrologic Cycle. in *Climate Science for Serving Society* 151–184 (Springer Netherlands, 2013). doi:10.1007/978-94-007-6692-1_6

25. Pinkse, J. The main excuses businesses give for climate change inaction. *Management Today* (2019). Available at: https://www.managementtoday.co.uk/main-excuses-businesses-give-climate-change-inaction/any-other-business/article/1585235.

26. Hall, J. W., Tran, M., Hickford, A. J. & Nicholls, R. J. *The Future of National Infrastructure.* (2016). doi:10.1017/CBO9781107588745

27. Stocker & T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. B. and P. M. M. (eds. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *CEUR Workshop Proc.* 1542, 33–36 (2015).

28. Liu, J. et al. Systems integration for global sustainability. *Science (80-.).* 347, (2015).

29. Britton, T. C., Stewart, R. A. & O'Halloran, K. R. Smart metering: enabler for rapid and effective post meter leakage identification and water loss management. *J. Clean. Prod.* 54, 166–176 (2013).

30. Voulvoulis, N. Water and sanitation provision in a low carbon society: The need for a systems approach. *J. Renew. Sustain. Energy 4,* 041403 (2012).

31. Wentworth, J. *The Water-Energy-Food Nexus.* (2016).

32. Defra. *The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting. Making the country resilient to a changing climate.* (2018).

33. Gersonius, B., Ashley, R., Pathirana, A. & Zevenbergen, C. Climate change uncertainty: Building flexibility into water and flood risk infrastructure. *Clim. Change* 116, 411–423 (2013).

34. Lempert, R. & Kalra, N. Managing Climate Risks in Developing Countries with Robust Decision Making World Resources Report Uncertainty Series. 9 (2012).

35. Hall, J. W. *et al.* Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info-Gap Methods. *Risk Anal.* 32, 1657–1672 (2012).

36. Haasnoot, M., Kwakkel, J. H., Walker, W. E. & ter Maat, J. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Glob. Environ. Chang.* 23, 485–498 (2013).

37. Jeuland, M. & Whittington, D. Water resources planning under climate change: Assessing the robustness of real options for the Blue Nile. Water Resour. Res. 2086–2107 (2014). doi:10.1002/2013WR013705

38. Daron, J. Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. *Clim. Change* 132, 459–473 (2015).

39. Andersson, E., Borgström, S. & Mcphearson, T. Nature-Based Solutions to Climate Change Adaptation in Urban Areas. 21, 51–64 (2017).

40. Liu, J. *et al.* Coupled human and natural systems. *Ambio* 36, 639–49 (2007).

41. Ofwat. *Resilience in the Round. Ofwat* (2017).

42. Brockett, J. . 'Systems thinking" helps build confidence in drinking water – WWT'. (2018).

43. Voulvoulis, N. The potential of water reuse as a management option for water security under the ecosystem services approach. *Desalin. Water Treat.* 53, 3263–3271 (2014).

44. Mohamad Ibrahim, I. H., Gilfoyle, L., Reynolds, R. & Voulvoulis, N. Integrated catchment management for reducing pesticide levels in water: Engaging with stakeholders in East Anglia to tackle metaldehyde. *Sci. Total Environ.* 656, 1436–1447 (2018).

45. Voulvoulis, N. The potential of water reuse as a management option for water security under the ecosystem services approach. *Desalin. Water Treat.* 53, 3263–3271 (2015).

46. Teytelboym, A. Natural capital market design. *Oxford Review of Economic Policy* 35, 138–161 (2019).

47. Voulvoulis, N. Water Reuse from a Circular Economy Perspective and Potential Risks from an Unregulated Approach. *Curr. Opin. Environ. Sci. Heal.* 2, 32–45 (2018).

48. Stahel, W. R. The circular economy. *Nature* 531, 435–438 (2016).

49. Karagiannis, I. C. & Soldatos, P. G. Water desalination cost literature: review and assessment. *Desalination* 223, 448–456 (2008).

50. Loftus, A. & March, H. Financializing Desalination: Rethinking the Returns of Big Infrastructure. *Int. J. Urban Reg. Res.* 40, 46–61 (2016).

51. Williams, J. & Swyngedouw, E. (Erik). *Tapping the oceans : seawater desalination and the political ecology of water.* (Edward Elgar Publishing Limited, 2018).

52. Massmann, G., Knappe, A., Richter, D. & Pekdeger, A. Investigating the Influence of Treated Sewage on Groundwater and Surface Water Using Wastewater Indicators in Berlin, Germany. *Acta Hydrochim. Hydrobiol.* 32, 336–350 (2004).

Acknowledgements

The authors would like to thank Alyssa Gilbert from the Grantham Institute for her work in editing and refining the paper. We would also like to thank Keith Colquhoun and Steve Kaye for reviewing the paper and providing critical feedback. Their review does not constitute an endorsement, and this paper does not represent their views.

CZ is funded by an Imperial College Skempton Scholarship and the Engineering and Physical Sciences Research Council (EPSRC; grant EP/L016826/1).

About the authors

Professor Nick Voulvoulis is a Professor of Environmental Technology at Imperial College's Centre for Environmental Policy. An environmental scientist by training, his areas of expertise revolve around integrated water and environmental management, especially where science and engineering interface with public policy. His research focuses on the interactions and interdependencies between human and natural systems, and the application of science to solve environmental problems and sustainability challenges. He is interested in research that can facilitate government policy development, create an environment for innovation, engage businesses, industry and the wider public while supporting policy makers defining better the sustainability challenges we face.

Charles Zogheib gained a degree in Civil Engineering (MEng with First Class Honours; Imperial College London). He is currently a PhD Candidate in water resources governance under the supervision of Dr Wouter Buytaert and Dr Ana Mijic at Imperial College. His work focuses on the link between data, evidence and good governance and is based on a case study of Quito, Ecuador. He has previously worked for Bechtel Corporation and Vinci Construction France. He has also worked on the problem of electricity provision in rural Rwanda.

About the Grantham Institute and Imperial College London

In 2007, the Grantham Foundation for the Protection of the Environment made the visionary decision to support an Institute at Imperial College London to provide a vital global centre of excellence for research and education on climate change. Ten years on, the Grantham Institute is established as an authority on climate and environmental science.

The Grantham Institute is Imperial's hub for climate change and the environment, and one of six Global Institutes established to promote inter-disciplinary working and to meet some of the greatest challenges faced by society. We drive forward discovery, convert innovations into applications, train future leaders and communicate academic knowledge to businesses, industry and policymakers to help shape their decisions.

Imperial College London is a global university with a world-class reputation in science, engineering, business and medicine, and excellence in teaching and research. Consistently rated amongst the world's best universities, Imperial is committed to developing the next generation of researchers, innovators and leaders through collaboration across disciplines.

www.imperial.ac.uk/grantham

Contact us

For more information about this subject, to discuss how the issues covered affect you and your work, or to contact the authors, please email us at: **grantham@imperial.ac.uk**