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PAPER

Pathways to different urban water futures: ‘silver baskets’ of sociotechnical solutions

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Keywords: pathways, decentralisation, water futures, urban water systems, participatory process

Abstract

The water sector needs advances in a range of thematic areas to deliver sustainable water systems in a future characterised by climate change, population growth, and ageing infrastructure. Individual innovations will not be enough to deliver the step-change required. A multitude of sociotechnical advances in water management exist, however the real innovation challenge lies in understanding and demonstrating how combinations of these solutions can be deployed to deliver resilient and adaptive urban water systems. These combinations, or ‘silver baskets’, need to be tailored to local needs and context and work synergistically with existing infrastructure. The scale at which the solutions will be deployed ranges from individual domestic applications to city-wide infrastructure, across potential water qualities ranging from black water for reuse and resource recovery to ultra-pure potable water. This paper describes the results from a structured set of workshops across five years with UK water sector stakeholders from more than 250 organisations to develop potential future scenarios and pathways towards each one for urban water systems. While there is value in the resulting ‘silver baskets’, arguably there is more value in building skills through the process of collectively envisioning future options, transition pathways and drivers, and understanding the range of possibilities and combinations to deliver sustainable water futures across an entire country’s water sector. The study concluded that all water futures lie on, and can be considered and planned for on, a continuum from centralised to decentralised, despite the variety and complexity of the pathways, contexts, situations and pressures leading to them.

1. Introduction

The water sector needs advances and developments in a range of thematic areas to deliver sustainable water systems in a future characterised by climate change, population growth, and ageing infrastructure. Many parts of the world will experience increased water scarcity (Gosling and Arnell, 2013) but regional climate impacts will be much more variable (Watts *et al* 2015). Providing clean drinking water, stormwater management, and wastewater collection and treatment at the current level of service is becoming increasingly difficult as populations grow and legacy water infrastructure becomes less reliable.

The global population will reach 10 billion by 2050, and potentially 16.5 billion by the end of the century, accompanied by a dramatic increase in demand for water and food. Fresh water is crucial, not only for drinking and household needs, but also to feed a growing population, industry, and both conventional and green energy supplies. For example, hydrogen production relies on large volumes of high quality water, requiring 17.5 l to 49.4 per kg of hydrogen (IRENA 2023), a factor which is uncertain and often not considered in most current water resources or renewable energy planning.

Increasing urbanisation will put added pressure on water networks and infrastructure. An estimated two-thirds of the world’s population will be living in urban areas by 2050 (United Nations 2018). The status quo for many cities is that centralised infrastructure provides water services, often transporting water long distances from sources, and returning clean but not pristine treated wastewater effluent to the environment. Surface runoff and sewer overflows further contaminate nearby water sources. Water infrastructure systems are ageing and deteriorating and will require unprecedented investment to be fit for the future. For example, leakage of water from ageing infrastructure wastes over 3 billion litres of water per day in the UK (Discover Water 2024) and the cost of replacing or renewing the 350 000 km of drinking water pipes seems insurmountable. At the current rate of investment, the legacy water infrastructure will be expected to continue to perform for decades if not longer.

Water management planning often focuses on the regional scale (e.g. Watts *et al* 2015), which omits consideration of the city scale buried infrastructure assets which represent up to 80% of the cost for adaptation and renewal (Hoffmann *et al* 2020). Understanding the options for future configuration of these piped networks is therefore crucial for developing water infrastructure plans at the city scale. The concept of integrated urban water management, which incorporates demand-side management, non-traditional water sources, and fit-for-purpose decentralisation is growing in popularity but its focus and application remains strongest in water-scarce regions and within the modelling academic community (Mitchell 2006, Bach *et al* 2014). Similarly, the concept of water sensitive cities is built upon access to a diversity of water sources via centralised and decentralised infrastructure and this thinking has begun to be applied in a few cities around the world notably in Australia, Singapore and China (Wong and Brown 2009, Wong *et al* 2020). There is a need to mainstream water sensitive concepts and to equip decision makers with the necessary knowledge and ways of thinking Wong *et al* 2020 Hoffmann *et al* 2020), especially in parts of the world that are not yet water scarce and therefore do not have first-hand experience with non-traditional approaches.

Individual water technology innovations will not be enough to deliver the step-change required to meet future pressures on water infrastructure. Many studies focus on the implementation of a single type of alternative solution such as green infrastructure (e.g. Li and Bergen 2018), which is useful but does not holistically consider the entire water cycle and infrastructure across a city. Water consumers view and interact with their water services in complex ways influenced by culture, the infrastructure itself, and how it is governed and regulated (Browne *et al* 2014). Social interventions, for example individually initiated and managed rainwater harvesting for outdoor water use, can deliver tangible results and must be considered alongside technological advances. Lock-in to specific ways of interacting with water is as strong in a social context as it is in a technological one (Hoffmann *et al* 2020). In this paper, therefore, we use the term 'sociotechnical solutions' to encompass the wide range of possible advances and innovations that might be applied across social and technical water infrastructure and interactions.

A multitude of sociotechnical advances in water management already exist, for example advances in treatment technology, sensors, and data services that provide water utilities and individuals with greater transparency about water use. But there is no 'one size fits all' technical or social solution that can ensure that all water services are resilient and adaptable to the pending future challenges (Wong *et al* 2020). The real innovation challenge lies in understanding how combinations of these solutions can be deployed to deliver resilient and adaptive urban water systems, which is noted by Hoffmann *et al* (2020) as one of the open research questions to be addressed in urban water management. The scale at which the solutions are deployed could range from individual domestic applications to city-wide centralised infrastructure, across potential water qualities ranging from black water for reuse and resource recovery to ultra-pure potable water. The water sector needs to be proactive in thinking through configurations and water qualities jointly with citizens rather than letting market forces and individual actions reshape the water infrastructure in an uncoordinated way (Li and Bergen 2018). The need for interdisciplinary and transdisciplinary collaboration and co-production or co-innovation is a consistent thread across the literature (e.g. Frantzeskaki *et al* 2019, Hoffmann *et al* 2020; Wong *et al* 2020) yet in practice it remains difficult to achieve at scale.

The aim of this study was to carry out a broad, sector-wide participatory process to collectively consider urban water system futures and to begin to develop a long-term vision, from the perspective of utilities that are centralised and not yet water scarce. Uniquely, rather than focusing on a single city as a case study, this process involved an entire country-wide water sector. A secondary aim was to identify combinations of solutions, or 'silver baskets', that were tailored to local needs and context and would work synergistically with the public and existing infrastructure to inform future research directions. Key outcomes for the study were to build skills across the water sector in conceptualising different water futures and considering urban water infrastructure as part of an integrated system. One element of the skills building was moving the mindset of participants away from the notion that a single 'silver bullet' technical solution could deliver a sustainable future. The participatory process was not intended to select a single best future silver basket but rather to begin the transition journey and equip participants with new knowledge and ways of thinking.

2. Methods

To usefully consider and assess different futures, it is essential to consider time frames consistent with the drivers of concern and relevant to the system being considered. It is also important to work at time frames

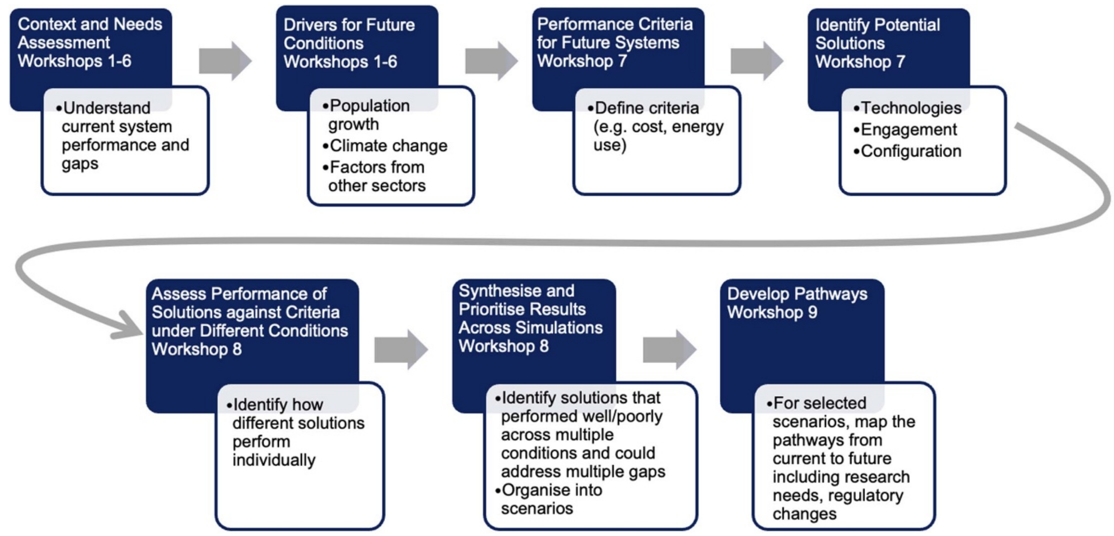

Figure 1. Overview of study methodology.

that can be imagined by all participants but which free participants from undue bias, preconceptions, or concerns about their immediate problems. The time frames must not be so large that thinking becomes pure fantasy. For water infrastructure systems subject to the pressures of climate change and changing population densities and growth, we selected a time horizon of 50 years into the future to meet and compromise between these requirements. Across the study, elements such as funding source (e.g. user rates, government, private industry), governance model (e.g. privatised versus government run), and regulatory regime were not explicitly considered to remove constraints about the type of solutions that might be possible.

The methodology for this study draws upon master planning principles that are typically used in the water industry to develop and test future scenarios (e.g. Simonovic 2009). As outlined in figure 1, the development of future scenarios begins with defining the context and current needs for the study, the drivers for future conditions, the performance criteria for the future system, and the potential solutions to be combined and tested. In a typical water master plan, the future scenarios would then be tested using simulation techniques, such as hydraulic modelling. However, there are no models that currently exist which encompass the entire urban water infrastructure in an integrated way. Therefore, drawing upon the principles of expert judgment (e.g. Goossens *et al* 2008) the collective expertise of a diverse range of workshop participants active in the water industry was used to make assessments. Within each workshop of this participatory process, innovative approaches were employed to maximise participation and creativity for all attendees (Birdi *et al* 2012, Jones-Chick *et al* 2022).

The discussion of context, needs, and drivers for the future of the water industry was conducted during 6 separate workshops spanning nearly 2 years. Performance criteria and potential solutions were then developed during Workshop 7. These solutions, individually and in groups, were tested to simulate their ability to meet performance criteria during Workshop 8. The results from this solution testing workshop were then analysed in Workshop 9 to brainstorm pathways that might take the water industry from the status quo to different water futures. Workshops 7 through 9 took place over a further 3 years so that, in total, the work presented here represents input over a 5 year period. All these workshop outcomes were then synthesised by the authors with input from the wider academic team (see Acknowledgments) to form the results presented in this paper.

To ensure that input and thinking was representative of the complete water sector, workshops were widely advertised through the TWENTY65 Grand Challenge Centre for Water (www.twenty65.ac.uk), were free to attend, and open to any interested attendees. Participation ranged from 40 to 100 people for each event and spanned water utilities, regulators, supply chain, consultants, academics, non-profit organisations, and students. Participants also spanned careers and experience to further avoid bias and preconceptions. Participants were not consistent across and between the workshops, ensuring a range of views were captured and to avoid bias and groupthink. The study had interactions with more than 250 organisations including policy bodies such as UK Department for Environment, Food, and Rural Affairs (Defra), UK All Party Parliamentary Water Group, Water Services Regulation Authority for England and Wales (Ofwat), UK Environment Agency, Drinking Water Inspectorate for England and Wales, and the Drinking Water Quality Regulator for Scotland; large companies such as Kier, Stantec, Murphy, and RPS; the UK water companies;

small and medium companies/organisations like ATI, Metasphere, EMS, HR Wallingford, UK Centre for Ecology and Hydrology, UK Meterological Office, and British Geological Survey; startup companies such as Datatecnics, Resomation, Energy Box, Greener Waste, and Tecta PDS; professional associations like the Civil Engineering Contractors Association, British Water, Future Water Association, UK Water Partnership, UK Water Industry Forum; international organisations including Global Water Council, Imagine H2O, Singapore Public Utilities Board, German Water Partnership, Water Start, World Wildlife Fund, and Blue Tech; and academic visitors from Japan, Korea, Canada, USA, South Africa, and Australia.

2.1. Context, needs, and drivers (Workshops 1–6)

The global context of climate change, population growth, and ageing infrastructure as outlined in the Introduction formed the basis of the context and drivers. This study and its participants generally focused on the UK context characterised by widespread centralised systems, with privatised ownership and operation of utilities. While experiencing some changes due to climate effects, the UK is not currently facing severe impacts due to drought, flooding, or temperature. Other parts of the world have adopted different configurations for their water infrastructure, such as use of reclaimed water for non-potable applications, but these are not yet common in the UK. The transitions and future pathways discussed in this study can be generalised to be applicable to many situations but the starting point for this study is centralised urban water systems. While it may seem excessive to have spent six workshops on these aspects, reaching consensus that was well understood by all and could be clearly and effectively articulated at future workshops was essential.

2.2. Performance criteria for future systems (Workshop 7)

The workshop to develop performance criteria asked participants to assume different perspectives from across the water industry: water company (utility), supply chain (engineering and manufacturing), citizen user of water, industrial user of water, and regulator. From each of these perspectives, participants then brainstormed metrics which would describe whether a water system was performing 'perfectly' for them. Each of 5 tables of participants (5–10 people per table) then grouped and categorised the metrics, identifying their top 3 high priority categories.

2.3. Identification of potential solutions (Workshop 7)

Workshop participants were asked to brainstorm new sociotechnical solutions that might help better meet the performance criteria. Users were not restricted to sociotechnical solutions that would fit only within centralised water systems but rather could, and did, consider a wider range of options that might work with different scales of water service provision and different qualities of water beyond potable and black water (sewage). Emphasis was placed on developing solutions in terms of outcomes and characteristics (e.g. low energy desalinated water) rather than specific (proprietary) technologies. A two-step exercise had groups develop individual solutions and then select groups of solutions, called 'silver baskets', which they felt would jointly achieve the best performance in terms of the criteria. The opportunity to revise the performance metrics based on this preliminary test of how they worked against plausible future solutions was then offered along with the chance to add new solutions. The solutions identified were collated and synthesised to form the basis for the subsequent workshop to more formally assess performance. Emphasis was on consideration of a broad spectrum of innovations and baskets. There was no intent or assumption that the workshop would exhaustively consider all possible relevant innovations.

2.4. Assessment of performance of solutions against criteria (Workshop 8)

This workshop began with a prepared list of sociotechnical solutions based upon the findings in the previous workshop. Participants (as with all workshops, some were present at previous events, others were new) were then asked to discuss and score individual solutions on a scale from −3 (not useful and/or may cause negative impact) to +3 (very useful and/or has a positive impact).

Following the individual scoring exercise, participants were then organised into groups which considered one of four sets of future conditions, as outlined in table 1, and were asked to develop silver baskets of solutions to best address each one. These sets of conditions considered three of the top drivers identified in earlier workshops: the availability of inexpensive, low-carbon energy; the level of investment available for water infrastructure (regardless of source); and the extent of water scarcity. Furthermore, to capture the effects of population density and related considerations, an urban/rural designation was included. New solutions were encouraged to be added to the preliminary list, even if they do not currently exist in an implementable form (e.g. low-energy desalination, autonomous pipe inspection and repair robots).

Table 1. Summary of future conditions used by workshop groups for testing and development of silver baskets of sociotechnical solutions.

Group number	Low-carbon, inexpensive energy availability	Level of investment available	Extent of water scarcity	Urban/rural
1	Low	Low	Low	Rural
2	High	High	High	Urban
3	High	Low	High	Urban
4	Low	High	High	Rural

2.5. Synthesise and prioritise results across simulations to develop scenarios (Workshop 8)

Once the scoring was completed for the individual solutions and the silver baskets which address the sets of conditions in table 1 were identified, the workshop participants then reorganised to combine all groups who had worked on a given set of conditions. This reorganisation allowed the opportunity for participants to compare, challenge, and document the reasons behind the selection of given combinations of solutions, especially the dependencies between different individual items. The participants also identified pathways that were emerging, such as the degree of centralisation of the water infrastructure.

The project team then synthesised the outcomes of this workshop, developing five future scenarios that encompassed the infrastructure configuration, the silver basket of sociotechnical solutions, and degree of centralisation.

2.6. Develop pathways (Workshop 9)

A final workshop was conducted so that participants could provide input on the mechanisms, decisions, intermediate steps, and links that might lead towards a given future scenario. Interactions between the future scenarios were also considered explicitly. The outcomes of this final workshop, with further refinement by the authors, are presented in the next section with a pathways diagram plus details provided for each of the five future scenarios.

3. Results and discussion

The following sections are organised to present the outcomes of the series of workshops in order (figure 1), leading to the development of five generalised scenarios which describe the configuration of infrastructure and the selected silver basket of sociotechnical solutions. The pathways that might lead to adoption of any of the five scenarios, and potential future interactions between the scenarios, are then presented and discussed.

3.1. Context, needs, and drivers

The overarching drivers of climate change, population growth, and ageing infrastructure were determined to play a large role in the need for future water solutions. Further pressures which were viewed as tactical drivers for the water industry include: water resource scarcity, investment level, condition and performance of legacy infrastructure, environmental and water quality degradation, energy cost and carbon impact, public awareness, regulations and policy for water and land, and skills and capabilities in the water industry. These tactical drivers were used in subsequent workshops.

3.2. Performance criteria selected for future solutions

The performance criteria workshop results are shown in figure 2, with scores for the top three criteria that would be prioritised by each of the five types of stakeholders. A maximum score of 15 in figure 2 would represent all 3 high priority votes from 5 stakeholder perspectives being within a single category. Financial, user satisfaction, and water quantity/quality metrics dominate the priority list of performance criteria categories across all stakeholder perspectives. Other metrics are still relevant, particularly those covering system flexibility and resilience, but were not selected as high priority across all stakeholder perspectives by the workshop participants.

Ultimately, the performance criteria selected for use in the solution testing exercises were measures of user happiness in several categories: (1) quantity and quality of service, where all user demands are met when they need water services and all quality regulations are met or exceeded; (2) environmental sustainability, where abstractions are sustainable, discharges do not pollute, and carbon footprint is minimised; and (3) financial sustainability, where sufficient funds are generated and/or available to ensure sustainable, reliable water services.

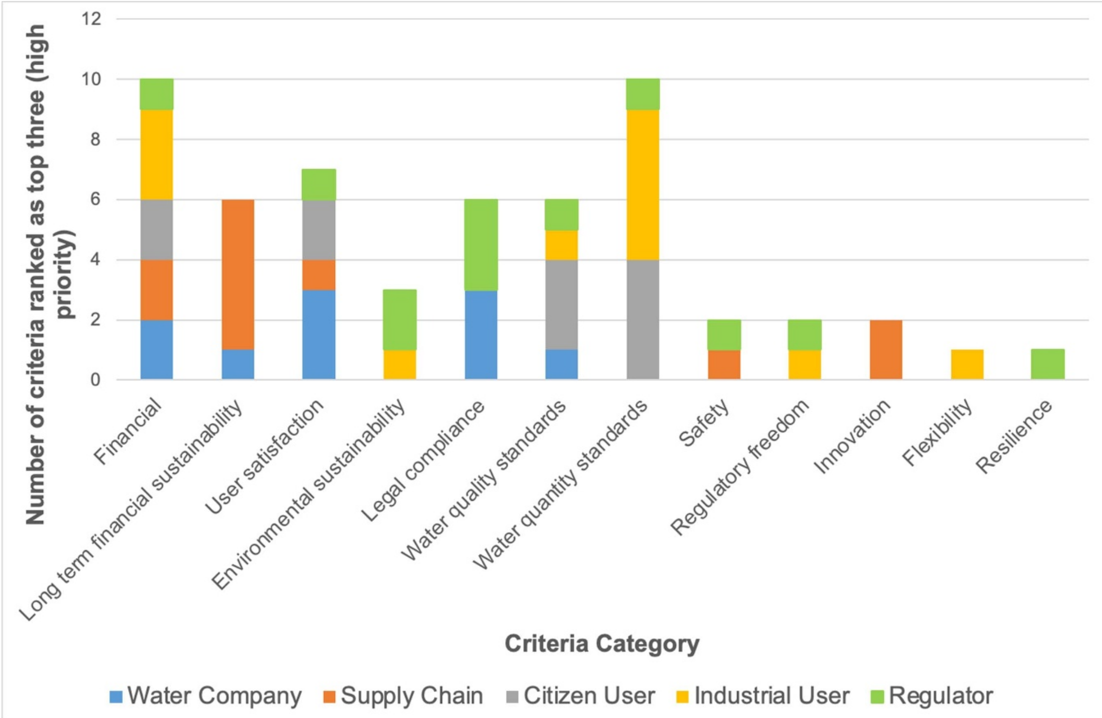

Figure 2. Summary of votes for top three (high priority) performance criteria categories by stakeholder perspective.

3.3. Performance of solutions against criteria

Workshop participants scored each individual sociotechnical solution on its future usefulness in general, with scores ranging from −3 (not useful and/or would cause negative impacts) to +3 (useful and/or would have positive impacts). Figure 3 summarises the average score for each solution. The solutions are broad categories and in many cases could comprise several different subcomponents using different technologies and/or human interactions. For example, 'smart appliances' requires not only the development and sale of advanced household goods such as washing machines and dishwashers with internet-enabled controls and centralised data management systems but also for households to purchase the appliances, enable the appropriate settings, and participate in water saving programmes. In a similar way, nearly all the solutions require elements of social and technical input into their design and application and as such are treated broadly as sociotechnical solutions. The workshop participants were explicitly directed to not consider barriers to implementation that might exist today but rather to focus on the potential utility and impacts of each sociotechnical solution were it to be implemented in the future.

Figure 3 shows that solutions which maximized the value from existing water infrastructure assets, such as sensors and real-time control systems, generally scored quite well. The scores also reinforce the concept that no one single solution will deliver the performance necessary to meet future challenges, with all but 3 solutions scoring higher than 1. The three solutions with low scores are ultra-pure treatment, energy from sludge, and low-energy desalination.

In discussion with workshop participants, the reasoning behind the low scores was drawn out. For ultra-pure treatment, participants felt that existing treatment was performing well and there would not be a need to pursue ultra-pure potable water above and beyond regulatory requirements. Energy from sludge was felt to be an existing and widely accepted current solution, at least in a UK context. Low-energy desalination was ranked as the least desirable solution mainly because participants felt that sufficient low-carbon energy would be available in future, via solar and wind power especially, that desalination energy requirements would not drive the need for new technologies.

3.4. Scenarios developed from synthesis and prioritisation of results across simulations

Once the individual prioritisation of solutions was completed, workshop participants then grouped solutions into silver baskets of highly performing solutions for their assigned future conditions (table 1). Solutions based on improved monitoring and management of existing infrastructure scored very well across multiple conditions, as was the case in the individual solution scoring. However, solutions that required significant changes to infrastructure or sector regulation scored differently across the future conditions. When

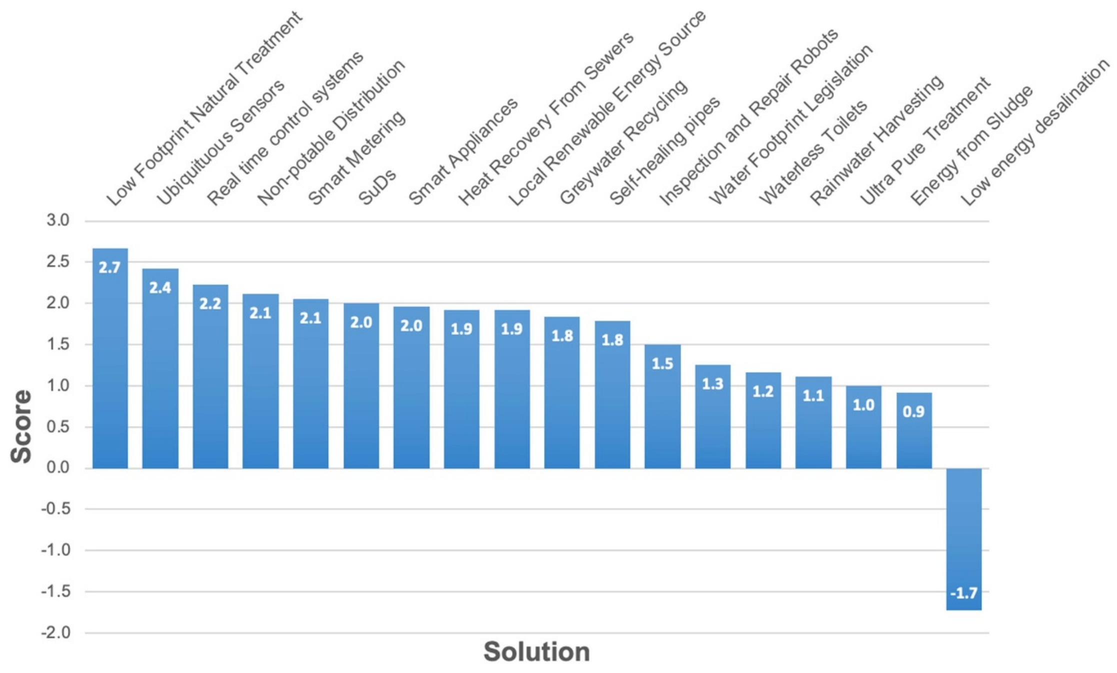

Figure 3. Summary of individual sociotechnical solution scores.

synthesising the results across the groups of participants, it became apparent that the largest differentiator between silver baskets across the range of future conditions was the extent of decentralisation.

A paradox exists in trying to select solutions which might perform well without considering the system configuration in which the solution will be applied. If the incoming water quality, desired output water quality, flows, and dependencies are known, the process of selection is fairly straightforward. For this exercise, solutions such as rainwater harvesting were desired by participants but do not currently fit well within a centralised water infrastructure configuration and raise questions about water quality produced, regulatory compliance, mobilising the public to assist with system installation and maintenance, and how the solution would interact with existing infrastructure. To broaden the possible universe of future water solutions, the centralised configuration of water systems must also be broadened.

To address this paradox and aid visualisation, a framework of different water qualities and different scales of infrastructure implementation was therefore necessary to facilitate the development of future scenarios that incorporate solutions at non-centralised scale and that consider a wider range of water quality than just potable water or sewage (black water).

Three different scales of urban water infrastructure implementation were incorporated into this framework: centralised (full city), community (tens to hundreds of households in one or many buildings), and domestic (a single or small number of households in one building). These scales are consistent with other studies but with different names, for example these scales correspond to hybrid, small grid, and non-grid by Hoffmann *et al* (2020). Across these scales, five different grades of water quality were considered: potable, treated but non-potable (e.g. reclaimed water), natural (e.g. lakes and rivers), grey water (e.g. discharges not containing fecal matter), and black water (e.g. sewage or other discharges containing fecal matter). These grades of water, drawing upon those considered by Makropoulos *et al* (2008), broadly represent the range of water qualities from potable to black water. When considered across the three scales of implementation, the result is a 3 by 5 matrix, which is a helpful framework for mapping urban water infrastructure and its interactions (figure 4).

In figure 4, the purest water quality (potable) is located in the top row in ranked order with the least pure water quality (black water) at the bottom. Treatment steps are indicated by vertical orange upward arrows from a lower to a higher quality. Use of water that degrades its quality (e.g. using the toilet) are shown as vertical downward arrows from a higher to lower quality. Infrastructure which delivers water to and from different scales across a city are shown as horizontal arrows. In a fully centralised system scenario as shown in figure 4, no treatment is taking place at the community or domestic scales. The community scale is largely ignored with the exception of localised outfalls from storm sewer systems to natural water bodies, which do not occur everywhere across a city and therefore impact certain communities more than others.

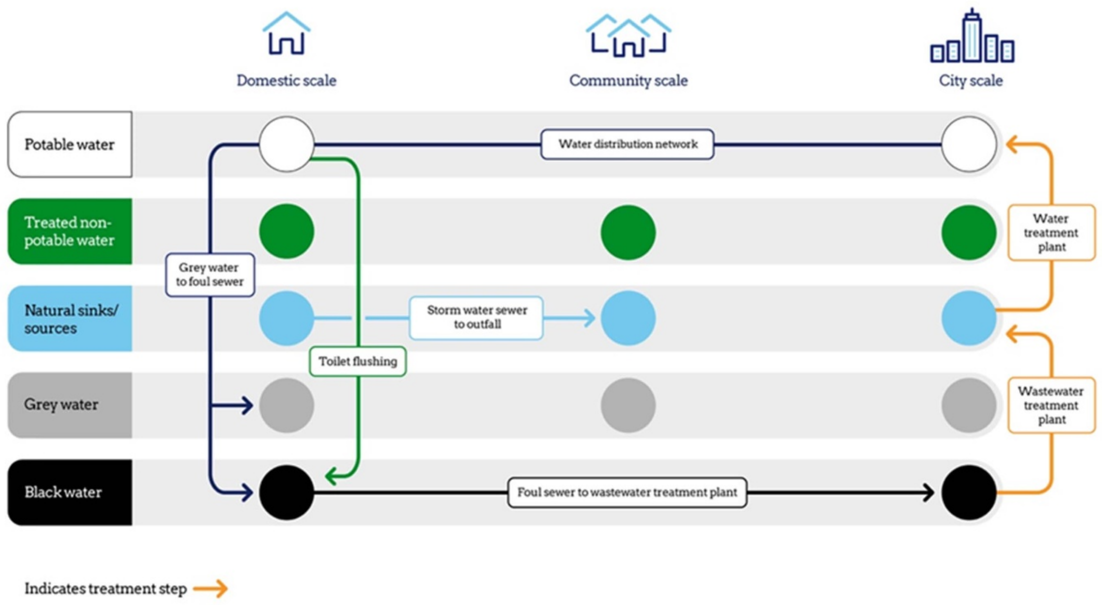

Figure 4. Schematic of 3 by 5 framework for infrastructure scale and water quality, mapping centralised water and sewer networks and treatment. Reproduced with permission from Twenty65, www.twenty65.ac.uk. Adapted from Hook *et al* 2018.

Applying this framework to synthesise the silver baskets of sociotechnical solutions from the workshop, five distinct future scenarios were developed ranging from fully centralised to fully decentralised water infrastructure configurations. This range can be considered as a sequence, or continuum, of configurations with different degrees and elements of decentralisation from one extreme (fully centralised) to the other (fully decentralised). These scenarios are not exhaustive, as many different configurations are possible along this continuum and even within the 3 by 5 matrix which is a simplification. The five scenarios presented were selected to be representative of the dominant silver baskets of sociotechnical solutions identified by workshop participants and the configurations for which these solutions would perform well synergistically.

3.4.1. Luxury centralised scenario

An obvious future scenario is to retain a fully centralised infrastructure configuration as shown in figure 4. With sociotechnical solutions to improve the performance of infrastructure and the happiness of users with the services provided, this scenario could leverage legacy infrastructure investment to meet all future performance criteria. For example, advances in proactive water main break detection and repair could prevent outages, thereby improving the performance of the network and increasing user happiness with uninterrupted service. The priority sociotechnical solutions within the silver basket for this scenario as selected by workshop participants included: autonomous inspection and repair robots to extract the full service life from buried infrastructure, self-healing pipes to extend their service life and reduce repairs, energy from sludge to take advantage of recovery opportunities at large scale wastewater treatment facilities, ultra-pure treatment at large scale treatment facilities to meet increasingly stringent criteria, smart metering for understanding system usage, real-time control systems for optimising system operation, and ubiquitous sensors to inform operation and planning. Social considerations noted for this scenario included issues around data ownership and the creation of public trust to support centralised decision-making and operations.

3.4.2. Point of use treatment scenario

Moving away from fully centralised, the next scenario considers the distribution of non-potable grade water in the current potable water network (figure 5), either in response to infrastructure degradation or inability to remove recalcitrant pollutants. In this case, treatment would be provided at the point of use for consumption purposes and may not be required for non-potable uses like toilet flushing. This scenario retains centralised black water collection and treatment, although with potentially more sewer overflows to the natural environment if infrastructure has become further degraded. This type of scenario currently exists, where degraded water infrastructure results in non-potable drinking water being distributed. Wealthier households who can purchase treatment systems are able to protect their health while poorer households without treatment can then suffer adverse health effects. While this configuration can be seen as

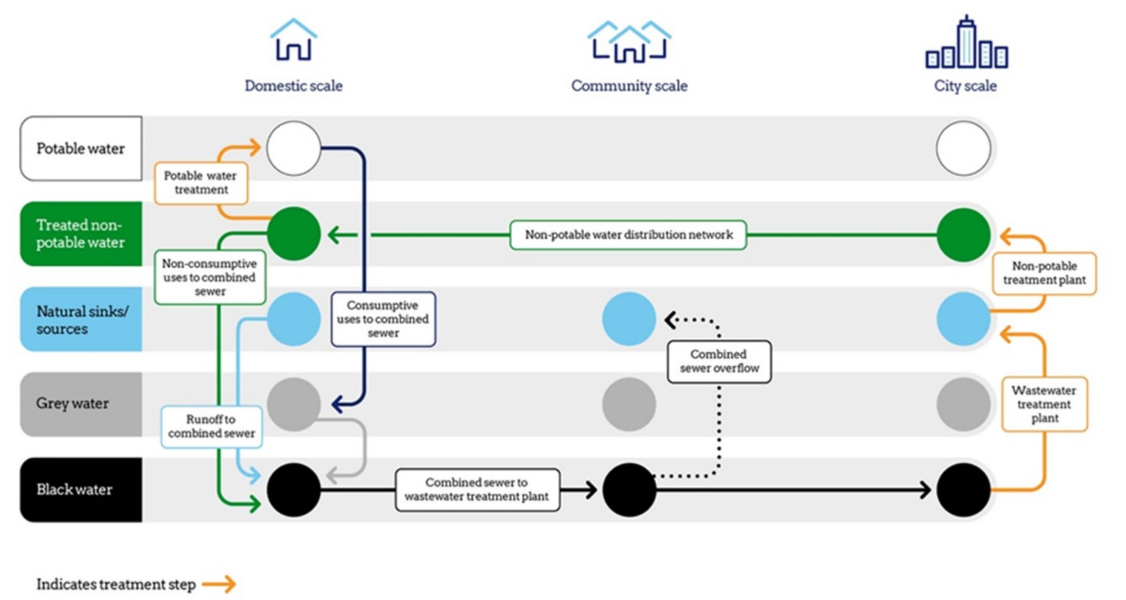

Figure 5. Schematic of point of use treatment scenario featuring city-scale distribution of non-potable water with domestic treatment at household scale. Reproduced with permission from Twenty65, www.twenty65.ac.uk.

undesirable because of the potential inequality, there could be versions of this scenario where the domestic scale treatment is provided and maintained by a water utility or private company, analogous to other domestic services like gas furnace maintenance contracts. This scenario defers the cost of upgrades to the centralised infrastructure, trading those costs for point of use treatment costs (typically borne by the consumer) and associated issues with maintenance of distributed infrastructure.

The priority sociotechnical solutions within the silver basket as selected by workshop participants included: point of use treatment technologies to sustainably deliver the required water quality for different purposes at domestic scale, ubiquitous sensors to monitor the degraded centralised infrastructure, and smart metering to understand usage across the system. Social considerations for this scenario included: ownership and maintenance of the point of use treatment facilities, concerns about equity of water service for those who cannot afford point of use treatment, regulatory compliance, and education about risks of unsafe water.

3.4.3. Dual distribution scenario

Another future scenario which retains elements of centralised water infrastructure is the dual distribution scenario, as shown in figure 6. This scenario requires construction of a secondary piping network to deliver reclaimed water to households for non-potable uses. This configuration has been used for decades in the USA and other locations internationally, especially in areas with high water scarcity for outdoor irrigation purposes (Okun 1997). For example, the state of Florida currently reuses an average of 34% of its treated wastewater effluent for non-potable uses, with many utilities achieving 100% reuse through thousands of miles of non-potable distribution pipelines (SWFWMD 2022). This scenario could be more widely implemented to provide indoor water supply for non-potable uses if building plumbing was configured accordingly.

The priority sociotechnical solutions within the silver basket as selected by workshop participants included: non-potable distribution solutions to ensure water quality given the higher nutrient levels inherent in reclaimed water, self-healing pipes to extend the service life of the pipe networks, inspection and repair robots to extract the maximum performance from the legacy infrastructure systems, ubiquitous sensors to understand flow and water quality dynamics, and dual-purpose centralised water storage and stormwater management facilities. Social considerations for this scenario included: education about risks of unsafe water, retraining of plumbers and related professionals to avoid cross-connections of the two distribution systems, and engagement with the perceived 'yuck' factor related to water reuse.

3.4.4. Community scale scenario

The next scenario moves further towards decentralisation along the continuum to partially integrate community scale treatment facilities and infrastructure within a centralised paradigm (figure 7). This type of configuration augments the centrally supplied potable water and black water infrastructure using

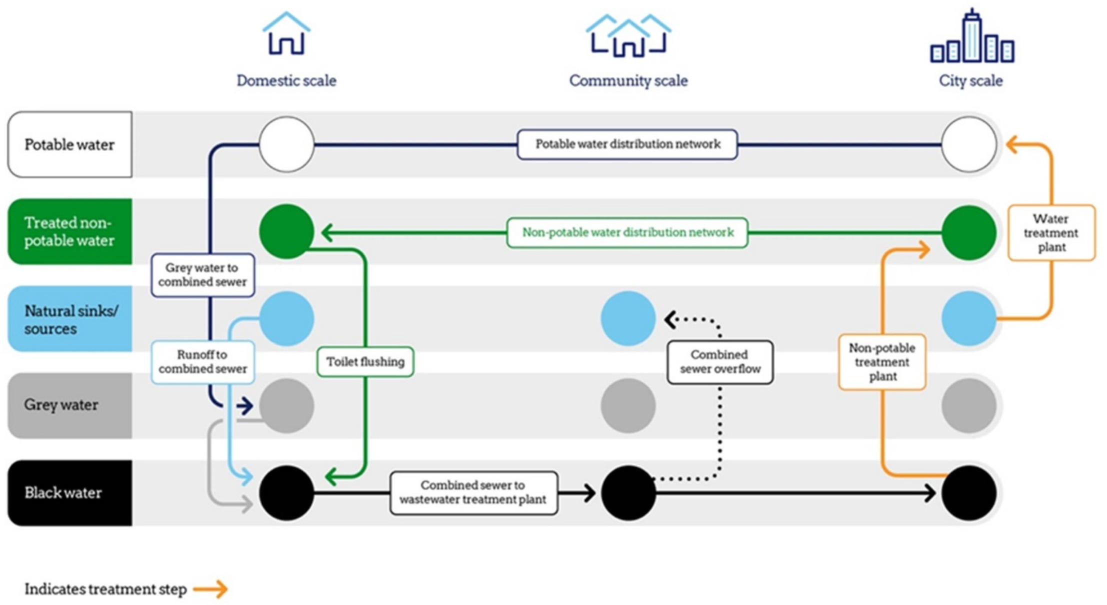

Figure 6. Schematic for the dual distribution future scenario featuring non-potable water distribution at city scale. Reproduced with permission from Twenty65, www.twenty65.ac.uk.

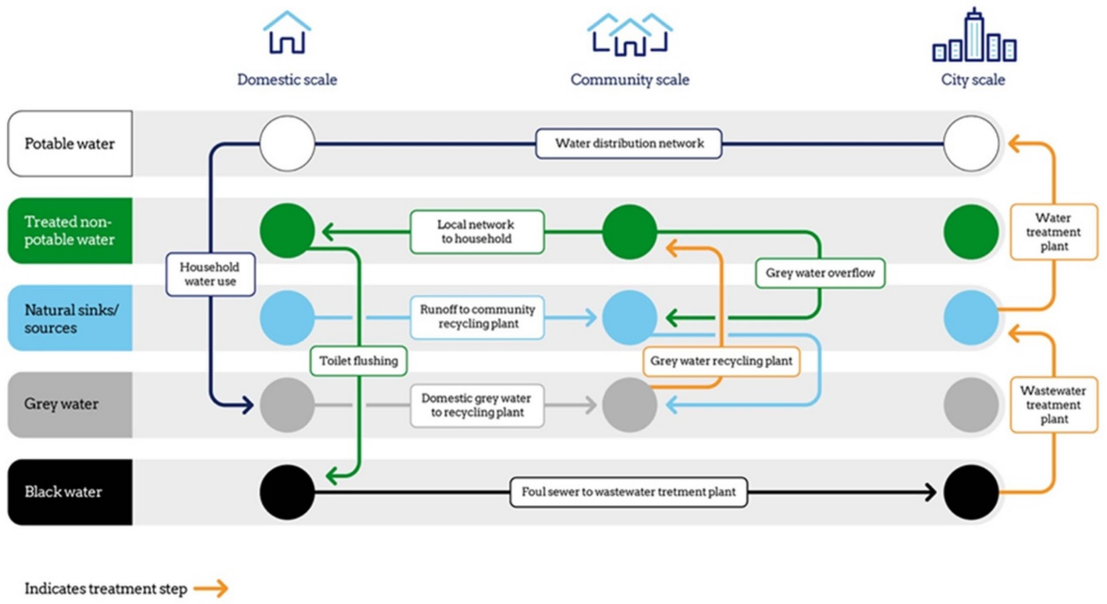

Figure 7. Schematic for the community scale partially centralised future scenario featuring grey water and storm water recycling at local scale. Reproduced with permission from Twenty65, www.twenty65.ac.uk.

community scale collection, treatment, and distribution. A common example of this scenario would be the installation of greywater recycling within a large apartment building or set of buildings, complete with additional piping at the local scale. In the example shown in figure 7, local stormwater is also diverted to community scale treatment for reuse. This configuration can reduce the pressure on existing city-scale infrastructure by reducing flows, which may support extending the service life of legacy pipe assets. The pooling of flows to and from multiple households at the community scale increases the resilience of the system to outages. An example of this configuration is the Central Park redevelopment project in Sydney, Australia where wastewater and stormwater are collected, treated, and delivered to different users (industrial, commercial, residential) across the 5.8 hectare site. The scheme supplies cooling towers, irrigation, toilets, and washing machines (CRC for Water Sensitive Cities 2025).

The priority sociotechnical solutions within the silver basket for the Community Scale Scenario as selected by workshop participants included: rainwater harvesting to capture local water resources for reuse,

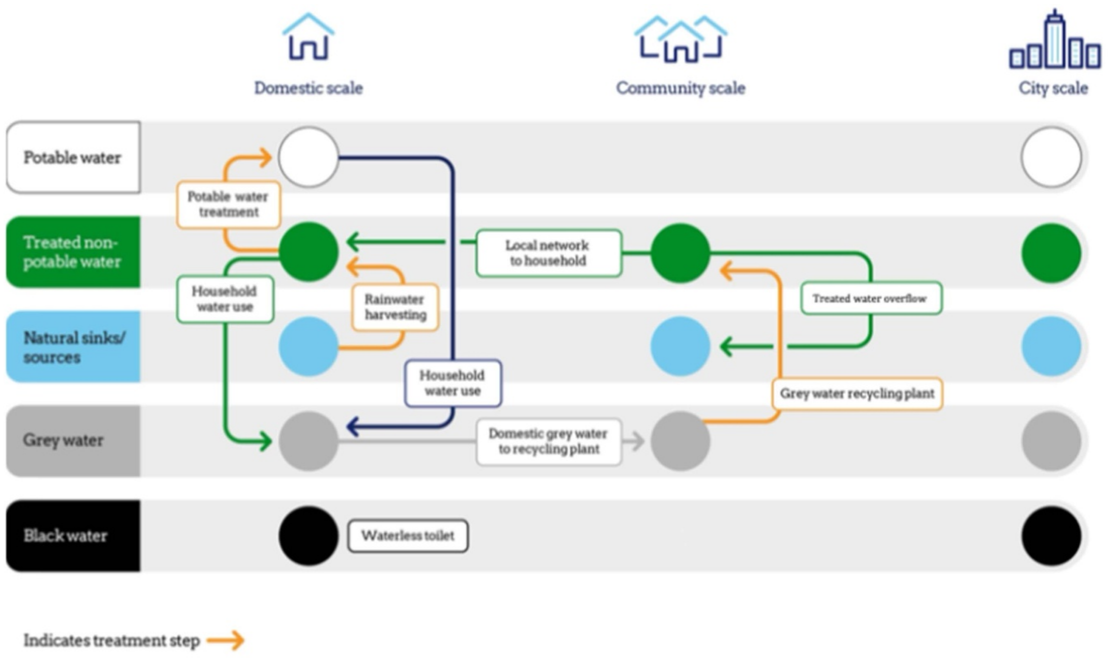

Figure 8. Schematic for the fully decentralised future scenario featuring domestic scale treatment supplemented by community scale pooled water resources and waterless toilets. Reproduced with permission from Twenty65, www.twenty65.ac.uk.

sustainable drainage systems to reduce pressures on legacy infrastructure, greywater recycling to provide acceptable water quality for reuse, and low-footprint natural treatment systems which would work well at community scale. Social considerations for this scenario included education about risks of unsafe water for consumers who are not familiar with different grades of water and plumbers who work on this infrastructure, and engagement around the perceived 'yuck' factor of reuse water.

3.4.5. Decentralised household scenario

The final scenario at the fully decentralised end of the continuum eliminates all city-scale infrastructure in favour of household-scale treatment, supplemented by community scale water resources to improve resilience (figure 8). This configuration with community-scale supplemental sources is more likely to occur than domestic-scale supplemental sources in an urban environment where individual wells or river intakes at every building would not be feasible. The true fully decentralised household configuration is commonly seen in rural locations where each building has the space and sufficient water supply for its own supply and disposal, i.e. a well and a septic tank. A notable aspect of this scenario in an urban context is the widespread use of waterless toilets to avoid the need for city-scale sewer infrastructure. Other domestic greywater is sent to community-scale treatment (e.g. for an apartment building or a neighbourhood facility) in this example configuration.

The priority sociotechnical solutions within the silver basket as selected by workshop participants included: rainwater harvesting to ensure maximum local water supply, greywater recycling to supplement local water supply, waterless toilets to eliminate the need for a sewer network, sustainable drainage systems to avoid the need for stormwater drainage networks and to supplement local water supply, point of use treatment technologies to sustainably treat domestic-scale water, and local renewable energy sources to power the water systems. Social considerations for this scenario included: the need for citizens to become actively involved in water management, and factors similar to the point of use scenario such as ownership and maintenance of the point of use treatment facilities, equity of water service, regulatory compliance, and education about risks of unsafe water.

3.5. Future pathways

The five different future scenarios served as representative endpoints to consider the pathways that might develop towards each one via three main drivers: centralised infrastructure failure, water scarcity, and availability of funding. The outcomes of the final workshop which considered these pathways are summarised in figure 9. The primary routes through the pathways diagram are representative of the types of drivers, decisions, and mechanisms that might result in a given outcome but these cannot include all local

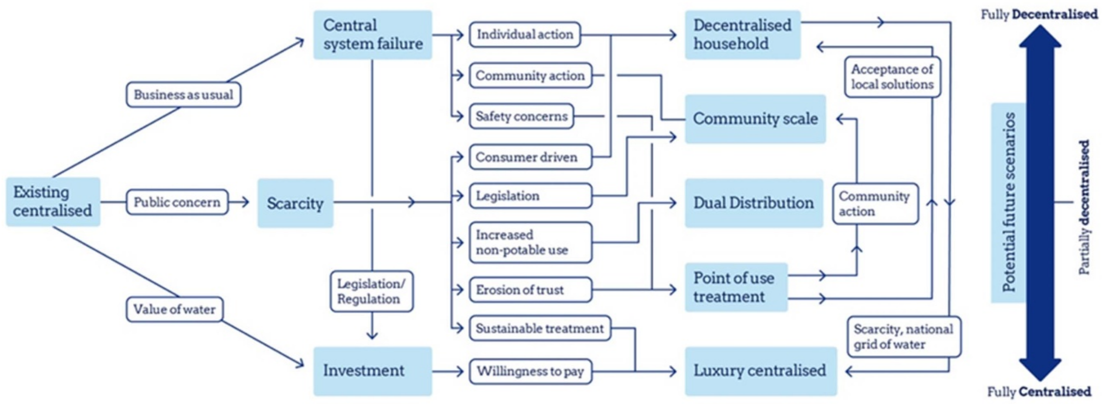

Figure 9. Pathways from existing centralised systems to five future scenarios. Reproduced with permission from Twenty65, www.twenty65.ac.uk.

considerations and thus are not exhaustive. However, these serve to spur discussion and expand the range of factors that might be considered for a given location in its future water system planning.

3.5.1. Pathway via central system failure

A baseline consideration must always be to do nothing and carry on with the 'Business as usual' pathway. For the UK this would mean carrying on with less than 1% asset renewal leading to increasing failure rates. Extrapolation of this situation leads to the worst-case scenario of catastrophic 'Central system failure'.

From 'Central system failure', one response to increasingly unacceptable levels of service and environmental impact along this route could lead to top–down measures of strict regulation and governance that would ultimately force mass investment in renewal of water infrastructure. Water users might be effectively forced to accept increased bills to mitigate unacceptable service, thus providing a route to a luxury centralised scenario.

Alternatively from 'Central system failure', a lack of timely central action could lead to individuals and/or community groups deciding to take action on a pathway toward the decentralised or community scale scenarios and their corresponding silver baskets. Individuals might band together to find local solutions at various scales (e.g. multiple houses to villages). This route is likely dominated by wealthier individuals or private service companies providing water, treatment, and waste services with responsibility for the safety of these systems. This could lead to inequality with poorer individuals unable to afford the systems or services, as is seen in the Global South. Systems could however ultimately be managed by a central authority of some type (public or private) to address this inequality.

If water safety concerns become particularly dominant along the 'Central system failure' pathway, the response could be towards individuals opting for increasing personal control and responsibility for their safety and wellbeing via point of use technologies and hence arriving at the point of use treatment scenario. It should be noted that reaching this type of scenario via this pathway could lead to continuing unacceptable environmental impacts as well as inequality. This could also be the response route if cost-benefit indicates that it is cheaper to install extra treatment for potable uses and distribute second grade quality water in the centralised system (which is in poor condition) for all other uses. Thus, a more centrally driven move towards point of use treatment scenarios might emerge where the provision and maintenance of point of use treatment becomes regulated and a service provided to all to avoid inequality.

3.5.2. Pathway via scarcity

A second commonly identified main pathway was increasing public awareness and concern, particularly about the availability of water as the impacts of changing climate and increasing populations and increasingly dense populations are felt ('Scarcity'). This perception and appreciation of scarcity could lead to various responses. Where the response is driven by individuals ('Consumer driven') the likely response is towards household scenarios. This outcome is also likely to be coupled with increasing environmental awareness including the high chemical and energy costs to treat and move water and the use of high quality water for low grade end uses like toilet flushing. This situation could drive individuals to take action via 'Decentralised household' solutions including grey water and rainwater storage, treatment and reuse. Thus, this water pathway may also be influenced by social movements related to energy, plastics, environmental degradation, and climate. This response is likely dominated by bottom–up action for existing domestic buildings but could also include top–down legislation for new construction.

Alternatively, if public concern about scarcity also encompasses wider environmental concerns, then public pressure could lead to regulatory change ('Legislation) that advocates the right water quality for the right purposes. Coupled with energy and chemical use concerns, this pathway could enable community-scale systems to be developed that closely match the water quality to the type of use locally.

Another response path from increased public concern about scarcity could be 'Increased non-potable use' across more than just domestic buildings, such as through commercial drivers from industry. This situation would need the development of a market/demand for reclaimed water and associated regulations, but these exist internationally in the EU, US, and elsewhere. Thus, the dual distribution scenario might start to become prevalent. If this driver is coupled with overcoming public concerns for the 'yuck' factor associated with reclaimed water to add some public willingness to pay, then there could be sufficient financial support for the infrastructure construction of dual distribution to become widespread. An interesting unintended consequence here could be adverse impacts due to lower flows in existing urban potable water networks.

A wide public concern about water scarcity could also manifest as an 'Erosion of trust'. A likely response to this situation would be increasing adoption of point of use treatment due to concerns about drinking water quality. Thus individuals would take responsibility for drinking water quality but rely on central sources for quantity. This scenario would likely also lead to better matching of water quality with use, reducing the need for chemical and energy for centralised treatment, and reducing the burden of ever more intensive treatment to remove emerging and trace contaminants.

A final response that emerged on the 'Scarcity' pathway in several of the workshops/groups was related to technological breakthroughs in centralised sustainable treatment solutions, with dramatically reduced energy, chemical and environmental impacts. Such technologies also frequently included enabling direct reuse, which if again coupled with overcoming the 'yuck' factor, could enable a transformation towards a luxury centralised scenario, but in this case systems that are much more loosely reliant on the environment with minimal abstracts and returns.

3.5.3. Pathway via investment

A third main pathway from the current system state that emerged multiple times during the various workshops was one where the perception of the 'Value of water' is changed. This change could occur via various routes, from bottom–up community campaigns to centralised messages and everything in between. The net result might be a willingness to invest in water services and infrastructure that most naturally leads to a luxury centralised scenario.

The 'Value of water' pathway could also drive a move towards community-scale scenarios, for example by an appreciation that it is cheaper, easier, and more desirable to recycle water locally for non-potable uses than to pump from a distant central source (or pay for new central sources). This community-scale reuse scenario helps reduce water discharges to the environment, with discharged water resources valued and perhaps even traded. These scenarios also require mechanisms, including regulatory, to be in place for communities to organise themselves to install and maintain the necessary systems.

3.5.4. Transitions between future scenarios

Five future scenarios have been mapped together with some of the main pathways that might lead to them (figure 9). However, this diagrammatic display should not be confused with thinking of scenarios as ultimate end points, or final solutions. History clearly demonstrates is that there is a continual interaction and evolution of infrastructure systems and how they are used (Brown *et al* 2009). The arrows on the right-hand side of figure 9 attempt to capture some possibilities of how these scenarios might further evolve as pressures, behaviour, and attitudes continue to change and the infrastructure systems and their use evolves. For example, coming from a decentralised household scenario where inequality was rife and climate change extremes of flooding and drought become even more prevalent, central action might take place to develop a national grid of water for regional sharing of water resources, thereby leading a transition back towards a luxury centralised scenario. Considering figure 9 in its entirety, it can be seen that all water futures reside somewhere on a continuum between fully centralised and fully decentralised and that the preferred solutions for a given situation, context and time horizon can be mapped and planned for on this basis.

4. Conclusions

The results of a 5 year, large participatory workshop process drawing upon participants from across the UK water sector to consider the future of sustainable urban water infrastructure have revealed several key findings. Water futures coalesce onto and can be usefully planned for and anticipated by consideration of a continuum based on the degree of (de)centralisation. There is no single silver bullet for sustainable resilient water infrastructure that is robust and resilient to likely future pressures, including climate and population change as well as ageing infrastructure. Rather the water sector needs combinations, or silver baskets, of sociotechnical solutions and innovations. But there is no one silver basket, either. Futures will be different in each urban context, with beneficial scenarios matched to the local needs and working synergistically with existing infrastructure. Considering not just the future silver baskets as endpoints but also thinking through the pathways by which each scenario might be reached was an important element of the study to bring participants along on the journey and better link the futures to the current situation.

In all scenarios, participants felt that there was too much value and intrinsic familiarity of use by citizens within the existing infrastructure systems for them to be abandoned rapidly. Rather, a transition might slowly evolve the urban water infrastructure configuration in response to different drivers. How citizens interact with water infrastructure was key in all scenarios. While this study did not look explicitly at governance models, regulation, financing models, and political/cultural factors, these will be required as well as other studies have highlighted (e.g. Kiparsky *et al* 2013). Clearly, in each local situation, particular economic and governance factors will play a large role in the pathway selected. But given that examples of nearly all scenarios are currently in operation in some part of the world, the issues around governance and cost are not insurmountable. If certain future solutions become popular, supply and demand dynamics may result in cost savings.

The participants in the workshops predominantly represented a UK perspective, where centralised systems dominate and water scarcity is not yet extreme. Many participants were surprised to discover that most elements of the future scenarios were already in use somewhere else in the world, albeit not always in the most equitable or safe manner. In this way, one of the primary goals of the study to broaden the mindset of the participants to better understand non-traditional water infrastructure approaches was successfully met.

Thinking through the possibilities collectively, as was done in this study, is an important way to start grappling with future options and choices. None of the five future scenarios developed are likely to come to pass in the exact form presented. The sociotechnical solutions that were conceived and discussed are by no means comprehensive but served an important role in the co-creation and collaboration process to generate an essential shared vision of water futures, which will be required across all stages of research and innovation (fundamental to implementation) to achieve that vision. The success of this study derives from having a large, cross-sectoral critical mass of energetic participants working alongside a multidisciplinary research team within an environment designed to challenge conventions.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

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References

Bach P M, Rauch W, Mikkelsen P S, McCarthy D T and Deletic A 2014 A critical review of integrated urban water modelling—Urban drainage and beyond *Environ. Modelling Softw.* **54** 88–107

Birdi K, Leach D and Magadley W 2012 Evaluating the impact of TRIZ creativity training: an organizational field study *R&D Manage.* **42** 315–26

Brown R R, Keath N and Wong T H F 2009 Urban water management in cities: historical, current and future regimes *Water Sci. Technol.* **59** 847–55

Browne A L, Pullinger M, Medd W and Anderson B 2014 Patterns of practice: a reflection on the development of quantitative/mixed methodologies capturing everyday life related to water consumption in the UK *Int. J. Soc. Res. Methodol.* **17** 27–43

CRC for Water Sensitive Cities 2025 *Central park water recycling scheme* (available at: https://watersensitivecities.org.au/solutions/case-studies/central-park-2/)

Discover Water 2025 *Leaking pipes* (available at: https://discoverwater.co.uk/leaking-pipes)

Frantzeskaki N *et al* 2019 Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making *BioScience* **69** 455–66

Goossens L H J, Cooke R M, Hale A R and Rodić-Wiersma L 2008 Fifteen years of expert judgement at TUDelft *Saf. Sci.* **46** 234–44

Gosling S N and Arnell N W 2016 A global assessment of the impact of climate change on water scarcity *Clim. Change* **134** 371–85

Hoffmann S *et al* 2020 A research agenda for the future of urban water management: exploring the potential of nongrid, small-grid, and hybrid solutions *Environ. Sci. Technol.* **54** 5312–22

Hook J, Speight V and Mayfield M 2018 Framework for city-scale simulation of sustainable water technologies *Proc. of the 2018 IWA World Water Congress Tokyo*

International Renewable Energy Agency (IRENA) 2023 *Water for hydrogen production* (available at: www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production)

Jones-Chick R, Kelloway E K and Birdi K 2022 CLEAR IDEAS: can idea implementation training enhance the development of new ideas beyond idea generation training? *J. Creat. Behav.* **56** 79–91

Kiparsky M, Sedlak D L, Thompson B H and Truffer B 2013 The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology *Environ. Eng. Sci.* **30** 395–408

Li L and Bergen M 2018 Green infrastructure for sustainable urban water management: practices of five forerunner cities *Cities* **74** 126–33

Makropoulos C K, Natsis K, Liu S, Mittas K and Butler D 2008 Decision support for sustainable option selection in integrated urban water management *Environ. Modelling Softw.* **23** 1448–60

Mitchell V G 2006 Applying integrated urban water management concepts: a review of Australian experience *Environ. Manage.* **37** 589–605

Okun D A 1997 Distributing reclaimed water through dual systems *J. AWWA* **89** 52–64

Simonovic S 1989 Application of water resources systems concept to the formulation of a water master plan *Water Int.* **14** 37–50

South West Florida Water Management District (SWFWMD) 2022 *Reuse dashboard* (available at: www.swfwmd.state.fl.us/projects/reclaimed-water)

United Nations *68% of the world population projected to live in urban areas by 2050, says UN UN DESA | United Nations Department of Economic and Social Affairs* (available at: www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html) (16 May 2018)

Watts G *et al* 2015 Climate change and water in the UK—past changes and future prospects *Prog. Phys. Geogr.* **39** 6–28

Wong T H F and Brown R R 2009 The water sensitive city: principles for practice *Water Sci. Technol.* **60** 673–82

Wong T H F, Rogers B C and Brown R R 2020 Transforming cities through water-sensitive principles and practices *One Earth* **3** 436–47