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Need for Scaled Decentralized Water Infrastructure to Achieve Sustainability and Build Resilience

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Abstract

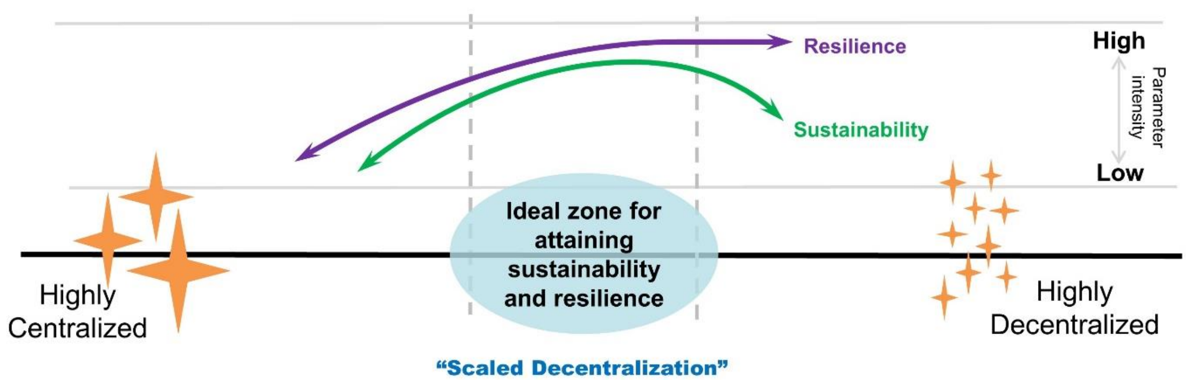
Urban Water Infrastructure (UWI) in cities faces enormous pressure to cope with increased water demands, handle extreme events and improve the service with minimum resource consumption and environmental impacts. The current study presents an approach for addressing the challenges in UWI, specifically in water supply and sewerage infrastructure. The article argues a need for a paradigm shift that simultaneously includes the sustainability and resilience aspects throughout the life-cycle of UWI. The article further highlights the issues in the prevailing approach of centralized infrastructure and demonstrates the necessity of moving away from such an approach and shifting towards decentralized infrastructure.

Understanding the factors accelerating decentralization to attain a paradigm shift to decentralization is necessary. Hence, the study first identifies the drivers of decentralization. Secondly, the need for an appropriate scale to be considered while implementing decentralized UWI is highlighted in this study. Further, the effect of the scale of infrastructure is discussed through the trade-offs between life-cycle costs, ease of governance, resilience and recycling benefits. The approach of scaled decentralization outlined in the study will be useful for developing countries to plan new infrastructure and also for developed countries to replace the aging UWI to create future sustainable urban systems.

Keywords

Decentralization; Resilience; Scale of decentralization; Sustainability; Urban water systems; Water and wastewater infrastructure

Graphical Abstract



1. Introduction

Urbanization has become a global trend of the 21st century. Due to subsequent economic development, the per-capita water consumption of the common person has intensified with the usage of appliances such as washing machines, dishwashers and showers (Roshan and Kumar 2020). Globally, the water crisis is a challenge in terms of quality and quantity, which is attributed to improper water management and infrastructure planning. Lack of adequate infrastructure creates hurdles for sustainable growth and intensifies poverty. Along with the advancement in economic infrastructure, the necessity of investing in social infrastructure i.e., education, health, water supply and sanitation, for sustaining economic growth has also been realized in recent times. Under consumer and political pressure, the municipal authorities (and utility providers) are obligated to supply water catering to the demands of citizens concentrated in urban clusters. The priority for clean water compels the municipal authorities to search for nearby surface water sources to create water supply infrastructure. Studies have shown that even if an economic and political will has enabled the use of resources for fetching freshwater or groundwater from long distances, 2 out of 3 cities cannot escape the water stress (McDonald et al. 2014). The cities using long-distance resources ultimately affect the ecology of rivers and streams subject to the excess withdrawal of freshwater and result in unexpected consequences such as shoreline erosion and stream depletion impacting human beings socially and economically (Leigh and Lee 2019).

1.1. Need for both sustainability and resilience perspectives

The prevalent urban water cycle is dominantly linear since used water is returned to the natural water bodies in an untreated form and freshwater is abstracted for non-potable uses. The prevailing linear economy of take-make-dispose is not sustainable, due to which a shift towards the circular economy is suggested to manage the water resources (Kakwani and Kalbar 2020). Additionally, the resilience of UWI has also become the focus of discussion recently. Hence, the current approach of UWI provisioning needs an assessment where sustainability and resilience aspects are evaluated.

It was only in the late 20th century that questions were raised on the prevailing development paradigm. Further, the significance of conserving the natural environment and including social aspects in planning was realized to sustain resources on the planet (Marques et al. 2015). Several organizations have acknowledged this need and have defined sustainability (Keeble 1988; Walker 1991; Hiessl et al. 2001). Additionally, in recent times, climate change has emerged as challenge of this century hence the other important aspect in infrastructure planning and development is resilience. Infrastructure systems presently face the uncertainty emerging from the planning and design stage, which is magnified due to growing climate change related stress (Bondank et al. 2018). Hence, environmental resource governance is observing a shift in focus from attaining only optimized and efficient systems to those capable of adapting during stress periods (Lawson et al. 2020). Moreover, it is not economically viable to design infrastructure to prevent failure from all possible disasters. Hence the concept of resilience has to be incorporated to achieve a good design strategy. From a systems and information engineering perspective, resilience has been defined as "the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks" (Ouyang et al. 2012). Adaptive and resilient approaches in all stages of an infrastructure project can minimize the effects of climate change and urbanization (Radhakrishnan et al. 2018).

With economic development on the rise, several cities are booming. However, the metro cities have been significantly impacted due to uncertain factors and are hence the most vulnerable. A conceptual framework has been proposed by Zhang and Li (2018) to capture the differences between urban resilience and urban sustainability. This framework characterized on two dimensions viz. 'rational-irrational' and 'active-passive' is based on the fact that resilient infrastructures may be unsustainable and sustainable infrastructures might not necessarily be resilient. It is the need of the day for urban practitioners to adopt rational urban development capable of achieving both urban resilience and urban sustainability (Zhang and Li 2018). In this context, UWI also needs to fulfill the expectations of sustainability and resilience. Sustainability is essential to make the water infrastructure affordable, acceptable, environmentally prudent and relevant for the given location. Whereas resilience in the water infrastructure is essential to cope with the emerging hazards related to climate change. The water infrastructure should have flexibility, adaptability and reliability to deliver varying service levels expected during emergencies.

1.2. Focus of the present study

The present work puts forth the sustainability and resilience aspects of UWI individually and discusses the significance of decentralized systems in adopting both approaches throughout the planning, design, implementation and Operation and Maintenance (O&M) of UWI. This study identifies the drawbacks of the conventional approaches of centralized planning of UWI and proposes a shift towards decentralization for achieving the Sustainable Development Goals (SDGs) and mitigating climate change. Further, the article identifies various drivers of decentralization to develop an understanding of decentralized water infrastructure's ability to achieve sustainability and resilience simultaneously. Prominently, the concept of incorporating the scale of decentralization in the planning aspects of UWI is introduced and emphasized. Stormwater is excluded from the broad scope of the article and the scope of UWI in discussion is limited to water supply and sewerage.

2. What's wrong with the current UWI

The current UWI is mainly focused on a centralized approach for infrastructure creation. Historically, such an approach had evolved to provide clean drinking water and maintain hygienic conditions in the emerging cities in the early 1900s (Luby et al. 2020). During that time, the cities and urbanization scale was not of the scale in current times. The centralized approach has commonly been adopted without thinking about the needs of the future scenarios after it achieved the expected results of controlling disease outbreaks. The centralized infrastructure approach is conceived and proliferated in developed countries and since colonial periods, it has been adopted in developing countries. Similarly, the wastewater treatment technologies that emerged in developed countries are being adopted in developing countries without considering the appropriateness of these technologies (Singhirunnusorn and Stenstrom 2009; Kalbar et al. 2012b). The disadvantages of centralized UWI are now evident (Jung et al. 2018; Eggimann et al. 2015; Libralato et al. 2012). Centralized systems are no longer deemed appropriate to address the challenges of UWI (Böhm et al. 2011) suggesting an urgent need to rethink how UWI is planned and implemented. The coordination among various departments in a utility becomes complex with an increased level of centralization, especially for large-scale systems. In extreme events, a centralized system might fail to deliver even a basic service due to the failure of critical routes. In contrast, decentralized systems cannot get support from other subsystems due to the absence of interconnections. Hence, a 'Centralized Control of Decentralized Execution' is an emerging approach that combines the advantages and disadvantages of centralized and decentralized systems (Diao 2021). The following sections describe the major lacunae in the centralized UWI by discussing the water supply and wastewater treatment infrastructure. In summary, the lack of a holistic approach in planning UWI is highlighted.

2.1. Water supply

The shrinking budgets for public infrastructures and lowering of subsidies amidst the massive cost of maintenance and restoration works make investments in centralized projects questionable (Eggimann et al. 2015). Mumbai city, withdrawing over 3220 Millions of Liter per Day (MLD) water from outside its boundary, ranks third in the list of top 20 urban agglomerations responsible for massive cross-basin water transfer to meet the needs of the urban population (McDonald et al. 2014).

2.1.1. Treatment

A major discrepancy posing problems in the funding of water supply projects is that government allots funds based on the current population whereas the treatment plants are designed for future population forecasted. Additionally, centralized treatment systems are more vulnerable to extreme events and lack of alternate water supply arrangements can cause severe inconvenience to the users. The recent example of the failure of Asia's largest water treatment plant in the Bhandup water complex in Mumbai clearly shows the impact due to the failure of a centralized system (Hindustan Times 2021). Water supply to the entire Mumbai region was affected as this treatment plant got inundated for the first time in its life due to the sudden heavy rainfall.

2.1.2. Transmission and distribution

Conventional water infrastructure is planned and designed on a largely centralized basis, and hence, efficient coordination among and within systems is essential, thereby making the operations complicated (Arora et al. 2015). Additionally, there is a risk of leakage during long-distance water transportation from the source to treatment facilities and households. Leakages have an economic and environmental impact on pipelines, resulting in considerable piping system expenditures. The leakages losses are estimated to be around 20%, whereas in some cases, it escalates to more than 50% of distributed freshwater (Haghighi and Ramos 2012; Ghorpade et al. 2021a). The significant variation in losses may be attributed to the age of the infrastructure system and the location. Challenges in monitoring a long network by a central authority increases the chances of illegal connections in centralized water supply systems as people deprived of water access resort to illegal means to extract water from municipal pipelines.

The large-scale centralized water supply systems tend to lose hydraulic efficiency as the network becomes unmanageable (Ghorpade et al. 2021b). Also, the service tanks in such systems are located outside the service zone, which is not an ideal hydraulic design (Kalbar and Gokhale 2019). The US Fire administration guidelines suggest adopting a decentralized approach for water supply provisioning and creating small-scale storage tanks instead of providing central storage with equivalent capacity (Harry 2008). Such decentralized systems will have net lower capital costs and will have many other operational benefits. For example, multi-outlet tank usage demonstrated by Ghorpade et al. (2021a) will help in the formation of district metered areas without numerous valve operations and achieving equitable water supply.

2.2. Wastewater

The challenges of the wastewater sector are severe as it is only visible developments such as infrastructure and water supply that receive priority from politicians and a lack of commitment by the government of developing countries is identified as the real problem in sanitation (Mara 2012). Further, to tackle sanitation issues, the provision of toilets is focused, whereas sewage treatment is neglected. Even if Sewage Treatment Plants (STPs) are constructed, the planning is not ensured from the perspective of sustaining technologies or operational and maintenance aspects of STPs. The incorporation of life cycle thinking in sewerage infrastructure planning is lacking, resulting in several obstacles or failures in achieving effective wastewater treatment.

2.2.1. Collection

The exclusion of sewage conveyance in the planning of STPs is a major hindrance that has resulted in the failure of centralized STPs. Research on the life cycle of conventional wastewater systems including sewers and STPs has shown the significant environmental impact of sewer infrastructure alone in both the construction and operation phase (Ranjan et al. 2019). The optimum degree of centralization depends on terrain conditions and settlement dispersion, with the latter having a prominent impact (Eggimann et al. 2015). A typical sewerage network consists of laterals, branch sewers and trunk sewer lines that ultimately deliver the sewage to the treatment plant. Gravity sewers are constructed at a slope and hence, the depth of sewer is proportional to the length of the network, reaching higher depths in a centralized system. The increased excavation for underground sewers results in high capital costs (Sood et al. 2021). Although centralized infrastructure helps achieve a greater scale of economy in treatment, it tends for diseconomy in the scale regarding sewer network construction where long distances have to be covered and vast volumes of potable water are required to keep the sewerage system clean (Libralato et al. 2012). Moreover, since almost 80% of investment costs are attributed to the sewer network, it becomes pertinent to give more importance to the economics of sewage conveyance in the planning phase (Eggimann et al. 2015).

There is a lack of scientific guidelines regarding effective and regular maintenance of sewerage and septage systems. Additionally, safety measures are often neglected during the O&M of sewers. Despite the prevalence of norms regarding usage of safety devices during sewage disposal, lack of stringent monitoring and authorization on the ground results in severe accidents onsite (Scroll 2019). Also, unregulated practices such as construction over sewer networks are prevalent in congested cities leading to accidents. The recent explosion underneath a private bank in Pakistan due to gas accumulation in sewers is an example of such unsafe practices (TOI 2021).

2.2.2. Treatment and disposal

The polluted water disposed by the cities in the downstream side is typically abstracted by cities located at the downstream end or used for irrigation purposes, which again can enter the food cycle. Thus, the cities do not have any incentives or obligations for reusing or recycling the wastewater generated and are not accountable for treating their effluent or recycling it. The World Bank considers unbundling of services as an opportunity to improve operational efficiency by introducing the private sector (Parkinson and Tayler 2003). In case of uncertainty and not reaching the expected urban growth, centralized systems tend to remain idle for long periods. For example, the Kamothe STP in Navi Mumbai, India, was designed for 80 MLD; however, currently, only 20 MLD of wastewater is treated and disposed of in nearby creek (TOI 2016). In these circumstances, the construction of smaller decentralized units tends to reduce the financial risks (Roefs et al. 2017) and achieve complete infrastructure utilization. The centralized STPs are commonly designed based on the conventional activated sludge process or the sequential batch reactor (CPCB 2021). Irrespective of the size of STPs, use of aerators in mechanized treatment systems consumes around 75% of energy during biological treatment (Maktabifard 2018; Kalbar et al. 2012a). As the energy delivered to the STPs from external grids is obtained through fossil fuels, wastewater treatment contributes to significant greenhouse gas emissions.

The treated effluent from centralized systems in developing countries such as India is commonly disposed of in nearby water bodies. Their distant location hampers the possibility of providing treated wastewater for secondary usage. The quantification of environmental benefits in decentralized systems is significant in economic feasibility assessments since centralized level reuse projects become economically viable only after considering environmental benefits (Kuttuva et al. 2018). On these lines, the need to implement circular economy principles of reduce, reuse, recycle, reclaim, recover, and restore has been identified for urban water management (Kakwani and Kalbar 2020).

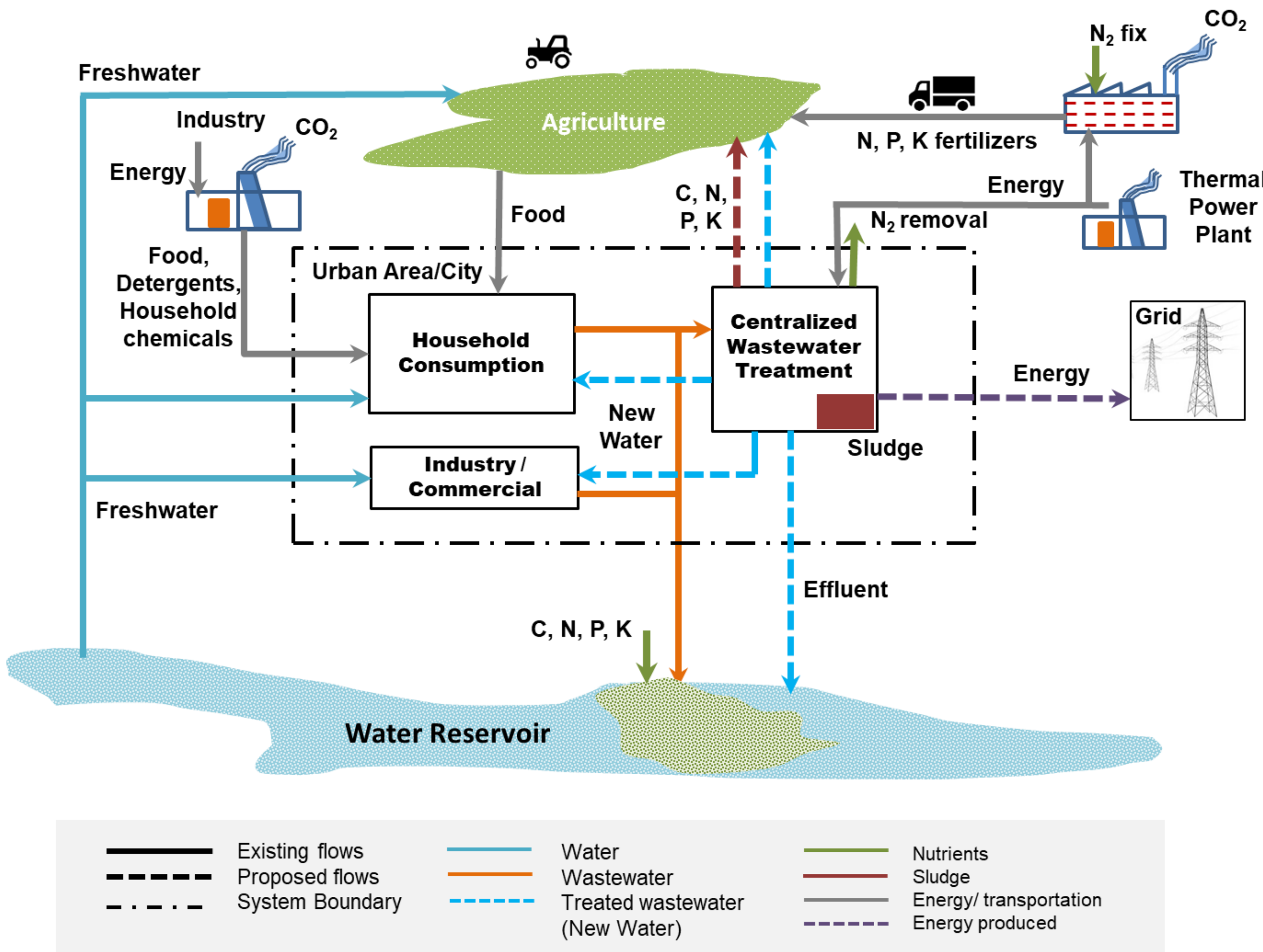


Fig.1 Energy and nutrient flows in a centralized urban system and envisaged changes

2.3. Lack of holistic approach for planning UWI

The present approach of water provisioning in cities and its implications on the environment is depicted in Fig.1. There is a common practice of transporting freshwater from long distances to meet the domestic, industrial and agricultural needs for the development of cities which involves huge transportation costs and consumes energy. Agriculture involves an indiscriminate use of artificial nitrogen fertilizers while nitrogen manufacturing utilizes 1-2% of the global energy supply (Batstone et al. 2015), making fertilizer production highly energy-intensive. Almost 60% of annual nitrogen consumed in food production is not recovered in usable forms or products and it accumulates in the soil or is lost in the environment (Mosier et al. 2004). Also, the soilless agriculture intensively practiced in urban areas relies on the use of inorganic fertilizers that consume the non-renewable nutrient phosphorus, thereby resulting in both local as well as global impacts (Arcas-Pilz et al. 2021). Further, urban citizens are increasingly consuming synthetic detergents containing phosphorus. Also, the food imported into the urban environment has increased the accumulation of nutrients in the cities (Wu et al. 2019). The excessive nitrogen and phosphorus concentrations in soil, water and atmosphere due to agricultural activities and synthetic detergent usage are causing nitrate pollution, eutrophication, and greenhouse gas emissions, respectively and eventually disturbing the natural nitrogen and phosphorus cycles (Cui et al. 2021). The stringent norms for nitrogen and phosphorus removal at the STPs demand the adoption of tertiary treatment processes requiring a significant amount of energy, as shown in Fig.1. Instead, the treated wastewater from STPs can be stringently monitored to meet irrigation water standards and thus be reused for agriculture. This practice will prevent additional expenses of removing nutrients from domestic wastewater and the use of nutrient-laden treated wastewater for irrigation will increase the crop yield. Further, studies have reported that fertilization with human urine from areas near the farms also uses less energy (Lima et al. 2020). Thus, instead of disposing of the treated wastewater in rivers, it can be used for non-potable purposes such as irrigation and toilet flushing, thereby reducing freshwater demand in agriculture. The saved quantity of freshwater can further be diverted for catering to the drinking water requirements of people who are still deprived of a clean water supply.

Wastewater treatment facilities should be looked at as factories manufacturing valuable resources in all three forms of solids, liquids and gases. There is a possibility of recovering energy as well as materials from STPs. Technologies such as anaerobic digestion, microbial fuel cells recovering energy and struvite precipitation recovering phosphorus, have been implemented at different scales in the urban settings. The use of byproduct sludge can become valuable in agriculture. Further, energy recovery can make the operation of STPs eco-friendly and financially viable. In this manner, incorporating circular economy principles for managing wastewater can transform sanitation into a sustainable service (Rodriguez et al. 2020).

Furthermore, apart from domestic sewage, the modern lifestyle of urban citizens has introduced emerging contaminants through pesticides, insecticides, toxic wastes from industries etc. Emerging contaminants are defined as any natural as well as synthetically occurring chemical or micro-organism that can potentially cause damage to the ecology or human health after it is received by the environment and is left unmonitored (Philip et al. 2018). A longitudinal survey along the Ahar river in Udaipur, India, has reported concentrations of emerging contaminants in the wastewater similar to those of high-income countries, even up to 10 km downstream of the high-density areas (Williams et al. 2019). The UWI in developing countries such as India should thus be capable of responding to upcoming challenges such as handling emerging contaminants.

The intrinsic limitations of centralized systems do not meet the expectations of holistic planning required for future-ready UWI. The new generation UWI should have the capability to address all the concerns of sustainability as well as resilience right from the planning stage. This is possible by shifting the current paradigm of infrastructure creation to decentralized systems. Decentralization is the only viable approach to overcome these issues, making decentralized UWI in urban planning a fundamental requirement.

3. Drivers for Decentralization

In the current scenario of India and other developing countries, the centralized approach has become a favorite of consultants, contractors, and politicians. It offers an opportunity to plan large projects, allowing all the stakeholders to utilize the funds in a single project proposal. Although this leads to great convenience for some stakeholders, such large projects result in wastage of financial and environmental resources due to the under-utilization of infrastructure in the initial years. For example, a recent report by the Central Pollution Control Board (CPCB), India shows that out of 1631 STPs (planned and installed) with a total capacity of 36668 MLD, only 1093 STPs are operational treating approximately 73% of sewage i.e., 26869 MLD sewage (CPCB 2021). On the contrary, well-planned and phase-wise infrastructure development will completely utilize the infrastructure and reduce the operational costs. Despite decentralized infrastructures gaining popularity, inadequate efforts have been made in developing planning tools to harness these opportunities. Apart from efficient resource utilization, there are numerous other benefits associated with decentralization, whose understanding will only escalate the adoption of decentralized UWI. Hence, some of the drivers who may accelerate the use of decentralized systems have been identified from the perspectives of sustainability and resilience and are discussed in the following sections.

3.1. Sustainability

The sustainability definition in the context of water infrastructure has been extended as "infrastructure designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity" (Marques et al. 2015). The triangular framework of sustainability based on economic growth and efficiency, social justice, and environmental protection is widely used for managing natural resources (Sahely et al. 2005). Further, the sustainability of any product or system has been commonly associated with the Triple Bottom Line (TBL) approach, including social, environmental, and economic dimensions (Marques et al. 2015), which is inadequate in addressing sustainability issues. Hence, subsequent studies have also considered technical and functional aspects such as durability, reliability, performance and flexibility (Rathnayaka et al. 2016; Kalbar et al. 2016). Sustainability is, thus, a critical perspective to be considered by planners and decision-makers while creating UWI. Achieving sustainability is one of the main drivers for decentralized UWI and it is gained by virtue of various factors which are described in detail in the Table 1.

Table 1 Sustainability aspects of decentralized UWI

Driver	Description
Economic benefits	• Increased capital cost of decentralized systems regarded as insurance as they reduce flood risk and associated economic loss in disastrous conditions • Life cycle costing accounting capital and operational expenses proves decentralized treatment systems based on natural treatment systems to be more economical
Social benefits	• Utilization of local labour and women generates employment • Delegating O&M authority to community imbibes sense of ownership that sustains STPs

	• Modular designs of decentralized treatment units relatively easy to install • Decentralized systems strengthen local government and achieve equity of resources
Market for recycled water	• The availability of treated water close to the end-use location avoids redistribution cost of reclaimed water (Point-of-sale reuse) • Decentralized systems suitable for mixed land-use pattern wherein a water exchange network can be established between residential, commercial and industrial thus reduce freshwater dependency
Resource recovery	• Wastewater and sludge are recognized as resource carriers amidst the energy-intensive production of nitrogen fertilizers and the depleting reserves of phosphorus rock • Plant-based solutions for phosphorus recovery from wetlands or algal ponds are an attractive option • Adoption of natural treatment systems in a decentralized manner can generate useful by-products such as fish feed, biomass, animal feed, biodiesel
Environmental impacts	• Global warming potential and eutrophication benefits facilitated by decentralized systems exceed the additional costs and infrastructure required by greywater distribution systems • Indirect emissions due to wastewater treatment infrastructure (especially O&M) constitute majority of the total emissions • Adoption of natural treatment systems in a decentralized manner has the potential to save energy and avoid CO_2 emissions in comparison to mechanized treatment systems

3.2. Resilience

Water sensitivity has become a key transition in urban areas, and accordingly, cities have begun to adapt to major changes happening in the world. The worldwide expansion of urban areas, population growth, limitations due to resource scarcity and the accompanying climate change have enhanced the need for resilient water systems. In the context of UWI, resilience refers to the ability of water systems to minimize the magnitude and duration of water supply service failure when subjected to extreme conditions (Diao 2021). In this regard, a paradigm shift occurred from fail-safe design strategies to safe-fail (resilient) design strategies, penetrating water infrastructure systems (Ahern 2011). Water infrastructure resilience is relatively a new topic in both research and industry and has been identified as a requirement for the future.

Resilient design systems aim to sense, absorb, and adapt to disturbances while maintaining essential functionalities (Leigh and Lee 2019). Resilience has been associated with characteristics such as robustness, rapidity or recovery, redundancy, reliability, buffering. The concept of resilience has multidisciplinary origins; hence leads to multiple interpretations. The changes appear to be gradual, with many cities still investing in traditional strategies. However, with a growing awareness of the importance of climate change, disasters, increased water demand, the urban communities are progressively expecting resilience in UWI to cater to the future uncertainties in urban water supplies. Spiller et al. (2015) have considered robustness, adaptive capacity and flexibility as the three main components of resilience.

The robustness of technical systems denotes their ability to function and perform to meet the set objectives even amidst changing environments and vulnerable operating conditions (Spiller et al. 2015). Robustness is the capacity of a treatment system to withstand a disturbance without entering a phase of unsatisfactory performance (Cuppens et al. 2012). For example, a robust water supply and sewerage infrastructure is that which continues to function satisfactorily till the end of the design period amidst varying loads, influent characteristics, and effluent quality standards. Interestingly, a resilient system is allowed to fail under extreme conditions, but the ability to recover quickly from stress and sustain the minimum functionality and service is referred to as adaptability or adaptive capacity. The time taken by the system to recover from a perturbation and regain its satisfactory performance plays a key role and is referred to as rapidity (Cuppens et al. 2012). Further, the flexibility of a system denotes the ability of the infrastructure to cope with changing operational conditions in response to emerging circumstances by entailing changes in scale, functionality, structure and operational objectives (Spiller et al. 2015). Flexibility refers to the ability of UWI to meet the newer guidelines with minimum infrastructural changes. It facilitates the integration of unpredicted advances in technologies such as easy retrofitting for resource recovery options or capacity expansion (Spiller et al. 2015). The advantages of decentralized systems with regard to resilience have been outlined in Table 2.

Table 2 Resilience aspects of decentralized UWI

Driver	Description
Robustness	• Decentralized systems less vulnerable to extreme weather events • Use of staggered systems limits the impact of system failures to smaller areas preventing domino effect among rest of the system components
Adaptive capacity	• Fixed design parameters in centralized systems are incapable of serving under uncertainties due to urban issues • Creating new infrastructure to continue the service provision in the case of failure can easily be achieved for decentralized systems of smaller capacity • Decentralized systems have greater adaptability and hence resilience as they can draw water from multiple water sources
Flexibility	• Centralized systems are often oversized due to provision of redundant pipes hence are expensive and futile • Significant idle capacity in the initial years to cater for future expansion • Decentralized systems facilitate flexibility by virtue of phasing out construction of wastewater treatment infrastructure with time • The learnings from localized problems can be incorporated while designing the future phases of decentralized STPs

4. Scaled Decentralized UWI

Decentralized UWI is attractive in multiple ways for all the stakeholders as they have the potential to achieve equitable resource distribution, SDG 10 (reduced inequalities), and SDG 6 (clean water and sanitation). Decentralized treatment can be an ideal pathway for establishing techno-economically viable wastewater treatment solutions in developing areas. However, the crucial challenge in implementing these systems is deciding the scale of decentralization.

Every engineering system has its own scale of economy, which offers economic benefits during the construction and operation. However, there are no further benefits associated with scaling up after achieving a particular scale. Also, the management-related challenges of decentralized infrastructure increase with the number of systems, subsequently escalating the maintenance cost in proportion. For example, Kigali city completely failed in handling on-site sanitation systems at individual and collective level (Kazora and Mourad 2018). Also, the effluent violation rates for small-sized plants (0.01 MGD) are reported to be 10 times higher than those observed in larger plants, exceeding 100 MGD (Vedachalam et al. 2015). Thus, too small systems also do not offer benefits due to the scale of economy nor attain the water quality standards; instead pose additional challenges related to the operation and governance of the system. With regard to integrated water and wastewater treatment systems, deciding an appropriate degree of decentralization for implementation has been identified as an engineering challenge (Woods et al. 2013). The issue of the scale of implementation has been pointed out to have significance in the implementation of decentralized systems (Arora et al. 2015). Hence, it is essential to plan the UWI so that maximum benefits of scale of economy are gained. Such a decentralized approach with an optimum scale of operation is essential for the smooth functioning of UWI (Kalbar and Gokhale 2019). Moreover, climate change, population expansion, and aging infrastructure pose unprecedented challenges to urban water systems in this century. With developed countries on the verge of replacing their age-old infrastructure amidst the systems outliving their initial design periods (Nikolopoulos et al. 2019), the proposed scaled decentralization can be used to replace the conventional UWI.

4.1. The concept of scaled decentralization

The distinction between centralized and decentralized treatment systems is depicted in Fig.2. Various definitions of the decentralized approach are documented in the literature and have been framed around population services or development characteristics. For example, Sharma et al. (2013) have defined a decentralized approach as the "water, wastewater and storm water services at property, cluster and development scale that utilize alternative water resources based on 'fit for purpose' concept". Libralato et al. (2012) have systematically defined various configurations of centralization and decentralization. Further, decentralized wastewater treatment includes systems that treat wastewater from small households or groups of dwellings and dispose of the effluent near the point of waste generation itself (Ranjan et al. 2019). Also, Paul et al. (2019) have proposed classification of centralization and decentralization based on potable and non-potable water reuse systems.

Decentralized systems are often considered equivalent to onsite treatment systems. Further, nature-based solutions such as constructed wetlands or waste stabilization ponds are also suggested as potential technologies that can be implemented in a decentralized manner. However, onsite or natural treatment systems are used in specific situations and cannot be solely categorized as decentralized solutions. Decentralized systems can operate at different spatial scales, viz., onsite scale (operated by property holders); cluster or development scale (operating under shared ownership) and distributed systems serving large developments (owned by water utilities) (Sharma et al. 2013). Decentralization cannot always be deemed small scale and needs to be context-specific (Libralato et al. 2012). Cluster systems are often used in communities and keep a balance between on-site and centralized treatment facilities (Vedachalam et al. 2015). Similarly, a semi-centralized approach has been suggested as a viable solution for old city centres as well as the growing expansions (Böhm et al. 2011). The scaling of semi-centralized systems has been of concern in their design for which the guiding principle is ‘‘as small as possible as big as necessary’’. In our study, decentralized systems are regarded as water supply or wastewater collection and treatment systems designed for the discretely selected population size to achieve the scale of economy at a given location and will henceforth be referred to as "***scaled decentralized systems***". Scaled decentralized systems are designed considering land availability, regulations, stakeholder interests and administrative boundaries. They have the advantage of diffusing the risk of extreme weather events, making them more climate-resilient. The focus of the current study is to bring out the importance of planning and implementation of scaled decentralized systems to achieve sustainable and resilient UWI.

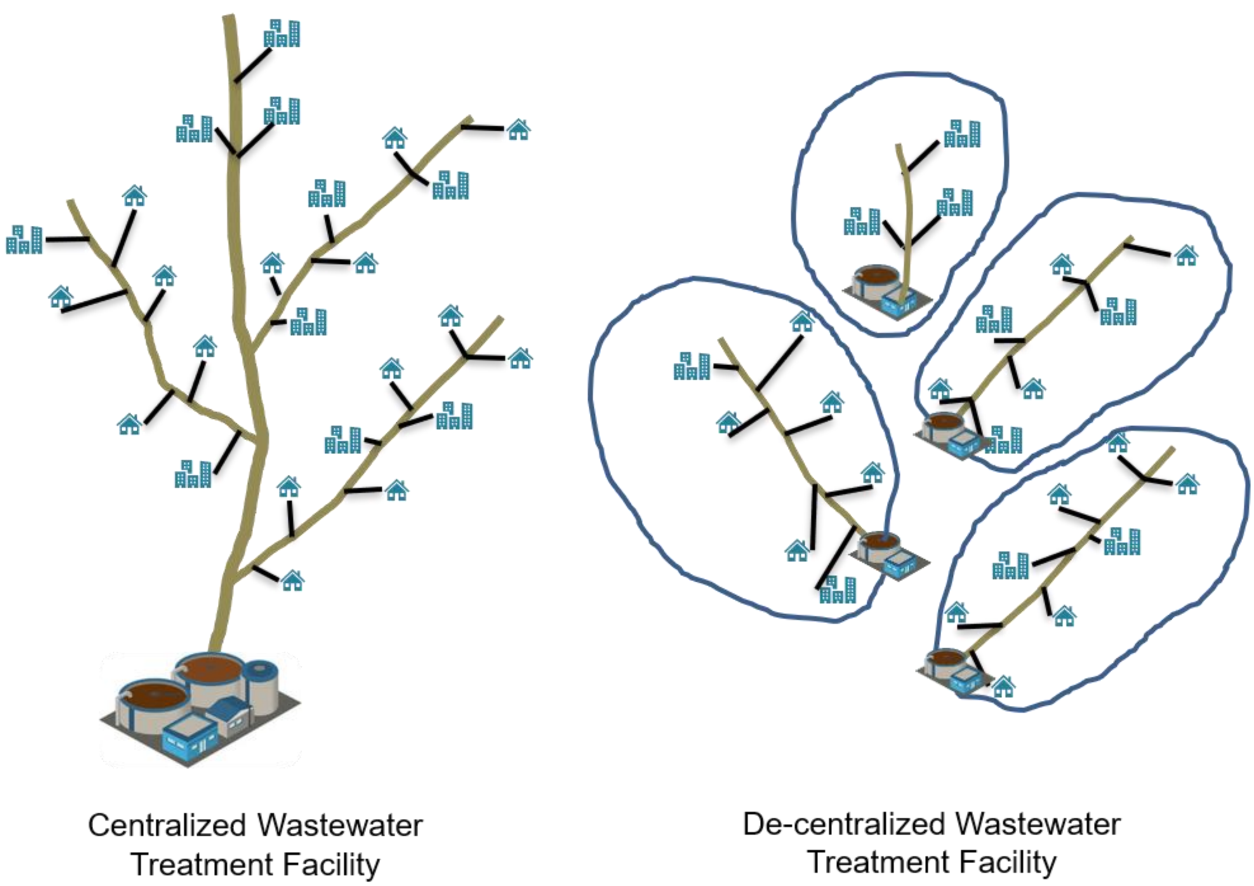


Fig.2 Centralized and decentralized infrastructure

4.2. Trade-offs between centralized and decentralized UWI

The trade-offs between adopting a highly centralized or highly decentralized UWI are depicted in Fig.3 based on nine parameters. In this figure, the sustainability aspect of UWI is discussed through five parameters, namely life-cycle costs, the potential for recycling water, resource recovery, social benefits, environmental impacts, while the resilience aspect of UWI is indicated through robustness, adaptability and flexibility. The previous discussion on drivers for decentralization of UWI indicates that the life-cycle cost (comprising both capital and O&M costs) of highly centralized and highly decentralized systems tends to be higher. Also, UWI planned in a decentralized manner provides greater opportunities to use recycled water and the use of treated water at the source, reduces the redistribution cost. Hence, the potential for recycling water is higher for decentralized UWI. Further, decentralized systems favor resource recovery due to a high recovery ratio. The operation and maintenance of resource recovery technologies is better sought at a community level than at household levels. While on environmental impacts of wastewater treatment, centralized systems tend to consume more energy and hence emit more greenhouse gas emissions. However, decentralized systems consume a greater quantity of materials and are hence associated with greater emissions from embodied in the materials used. As far as resilience is concerned, decentralized systems function well amidst changing environments and can resume service in less time than centralized systems. The decentralized UWI provide greater robustness, adaptability and flexibility than their centralized counterparts as already discussed in resilience aspects of UWI driving decentralization. Further, the coordination among the service providers is better managed in decentralized systems, and the O&M of such small-sized infrastructure systems is relatively easy. However, the complexity involved in outsourcing infrastructure projects increases for highly decentralized systems. Coupling the above trends, it is observed that the ease of governance tends to be on the lower side for both extremes of decentralized and centralized systems.

To holistically plan and implement UWI, the culmination of all the above parameters is needed. Hence, the trends of these parameters are collectively shown in Fig.3. In an ideal UWI, the sustainability and resilience of UWI should be the maximum, which can be only possible through scaled decentralization. As Fig. 3 depicts, the resilience of UWI increases towards decentralized systems and stabilizes after one point, whereas the sustainability decreases beyond one point. It is observed that the most economical systems having maximum benefits tend to fall somewhere between the highly centralized and highly decentralized systems. Consequently, the central zone becomes most favorable from the perspective of simultaneously achieving sustainability and resilience. This hypothesis is supported by the results of a comparative life cycle assessment of centralized, community, neighborhood and household scale that has shown the community level to perform better among others for the same treatment technology and end-use (Kobayashi et al. 2020). Also, amidst the high O&M costs making greywater reuse uneconomical at the household scale, the use of sewer mining at a neighborhood scale is suggested as a potential reuse scheme (Makropoulos et al. 2018).

Planning water reuse involves numerous decisions, for example, location, size, treatment technology selection, sewer size, appropriate end-use. Computing the tipping point where the advantages of peripheral water reuse will outweigh the benefits of centralized treatment is complicated (Woods et al. 2013). Amidst these practical difficulties, the author proposes using the scale of cities to determine the scale of decentralization for UWI. Unless such an appropriately scaled decentralization is adopted, the recycling of treated wastewater and resources recovered from the system cannot be economically redistributed and efficiently used.

Such an optimally scaled decentralized UWI will offer the following benefits compared to the prevailing centralized approach of UWI:

- Attainment of SDG 6 Clean Water and Sanitation, SDG 11 Sustainable Cities and Communities, SDG 13 Climate Action
- High flexibility which will address hazards emerging from climate change
- High adaptability will be useful for responding to different rates of urbanization in the city
- High reliability as at least some of the systems will function during the catastrophic events
- An opportunity for low-cost and land-based solutions for UWI
- Reduced O&M cost as phasing of the UWI is possible
- Opportunity to accelerate the circular economy in the water sector

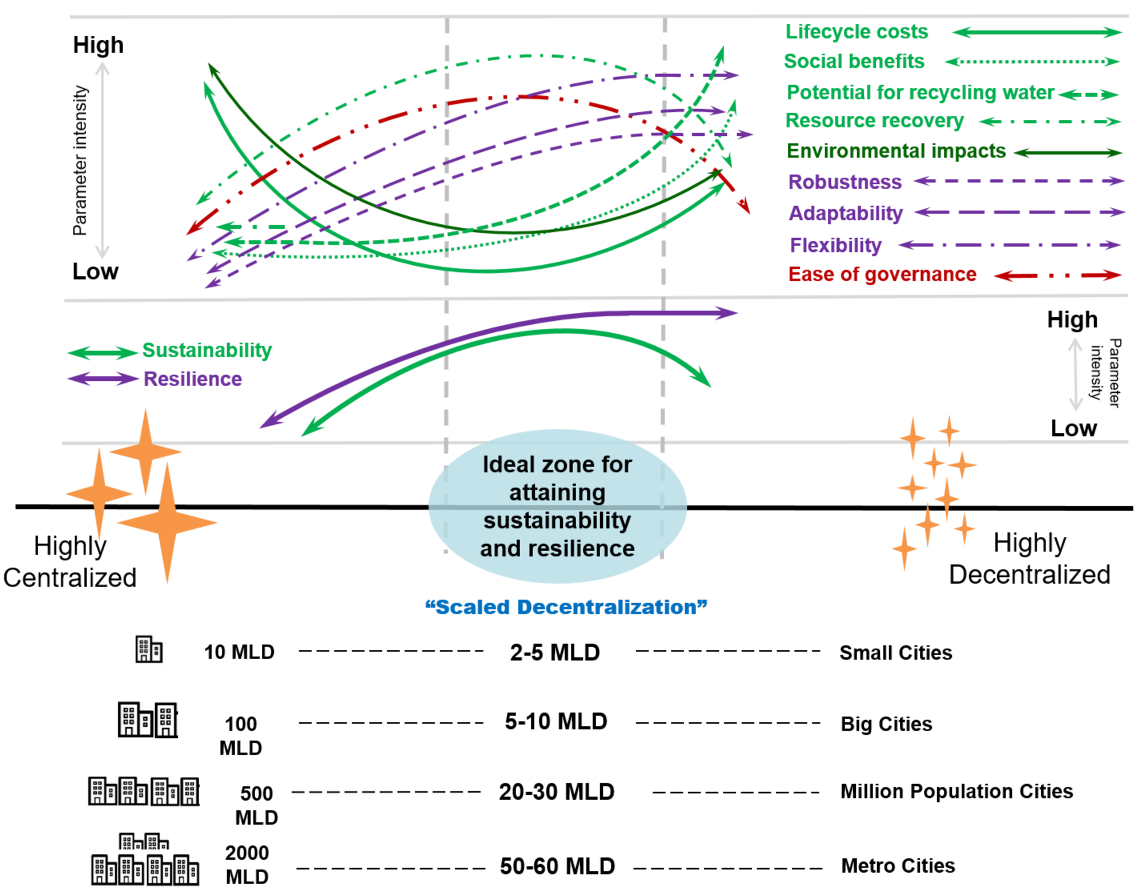


Fig.3 Scale of decentralization and ideal zone for sustainability and resilience

4.3. Lack of studies on decentralized configurations

Despite the growing inclination towards decentralization, the cost optimization of various decentralized UWI alternatives has not been studied in detail. Very few studies have used optimization models analyzing the cost of wastewater management systems across the varied extent of decentralization (Jung et al. 2018; Eggimann et al. 2015; Sood et al. 2021). Population density can be used as one of the criteria for determining the scale of decentralization. For example, (Mara 2012) has reported that beyond a population density of 160 persons per hectare, the conventional underground drainage system becomes more economical than onsite or decentralized systems. In another review study by Paul et al. (2019) shows decentralized treatment systems to have 2-3 times more costs than centralized treatment systems. Zanni et al. (2019) have demonstrated that the energy consumed in the distribution system plays a crucial role in the overall environmental performance. Ironically, the cost of the network is 70-80% of the total sewerage project cost which should actually determine the scale of the implementation rather than treatment plant costs. However, there are no such studies available and hence scaling factors for sewage collection networks are also not available.

There is no consensus reached due to the case-specific nature of the problem and also, there is a need to establish adequate knowledge through in-depth assessments. The 'optimal size' of a city has been discussed in academia, however, the question remains unsolved (Batty 2008). In the science of establishing the ideal size of a city, the role of physical infrastructure, particularly UWI is significant. The complexity involved in planning facilities at various scales in uncertain conditions necessitates using system-analytical tools complementing engineering decisions in this sector (Woods et al. 2013).

As there is no defined metric to determine the exact scale of decentralization of UWI, for every city a decentralization scale can be decided based on the scale of the city. For example, based on the author's experience and discussion with experts, a scale of decentralization is suggested depending on the size of the city and estimated sewage generation. Fig.3 shows that 2-5 MLD STP represents a decentralized treatment system for small cities, whereas 50-60 MLD STP serves as decentralized systems for metro cities. Thus, it should not be the absolute magnitude of plant capacity but the relative magnitude with respect to the size of the city that decides the scale of decentralization in UWI planning.

4.4. Technology choices for decentralized wastewater systems

There is a false notion of decentralized systems always being low-tech or nature-based solutions. However, a plethora of wastewater treatment technologies for decentralized infrastructure planning can be used. No one-size-fits-all technology might adequately satisfy the water supply or sanitation requirements across a region or country. Combinations of existing technological options should be strategically implemented after understanding the localized context in infrastructure planning.

Murphy et al. (2009) emphasized that "soft aspects" of wastewater treatment technology such as knowledge transfer mechanisms, capacity building and other social aspects need to be equally considered with physical properties "hard aspects". The study also mentioned that the situation or the context of decision-making decides the appropriateness of technology despite the proven success of technology in a lab or other field conditions. The appropriateness of technology has also been specifically validated in wastewater treatment by Kalbar et al. (2012), who emphasized that it is important to devise an overall strategy for wastewater treatment and not to focus only on technology. A highly mechanized decentralized system with a recycling network can also be appropriate given the conditions of the location e.g., highly dense urban area. One of the major obstacles in implementing this philosophy is the prevalence of a specific technology requirement clause in the bidding documents (tenders) that restricts the bidders from going for out-of-the-box solutions. The tenders of wastewater treatment projects should be technology-neutral and only focus on the water quality specifications and recycling requirements. The formulation of water policies regarding wastewater reuse and recycling have resulted in a rise in water reuse in Australia (Goyal 2022), which was attributed to the strong regulatory framework. From the above discussion, decentralized systems easily facilitate a market for recycled water, hence appropriate policies and framework for scaled decentralized systems is the need of the day.

Building on these arguments, the present study brings out an essential aspect in decentralized infrastructure planning: 'scaled decentralization'. The capacity of decentralized UWI might vary and the technology choice significantly depends on the scale at which decentralized infrastructure is practiced. In this regard, the common notion of onsite or decentralized treatment solutions being always low-tech and not matching the high-quality water requirement stands incorrect. A holistic understanding of the locality needs to be considered while planning a scaled decentralized UWI, which will offer both sustainability and resilience.

5. Conclusion

The evolution of water infrastructure historically is inclined towards planning and designing centralized infrastructure. The cities are currently going through changes such as urbanization and climate change that posed various stresses on the UWI. To cope with these challenges, there is a need for a paradigm shift in the way current UWI is planned, designed, implemented and operated. It is essential to consider sustainability and resilience perspectives while creating new UWI or retrofitting the existing UWI. The current centralized UWI does not allow enough opportunities for the water sector to practice a circular economy in the cities. Also, it is not economical and environmentally sustainable to recycle the treated water and create new water sources in the prevailing practice of centralized UWI. Moreover, centralized UWI does not offer any flexibility, adaptability and overall resilience, which have recently gained significance amidst the emerging extreme events due to climate change.

This study has identified the drivers for decentralized UWI such as economic aspects of the system, maximum capacity utilization, need for UWI of emerging towns, creation of a market for recycled water and overall sustainability and resilience for the system. The study also puts forth the need for considering the scale of implementation in decentralized UWI. The present work argues that along with an emphasis on decentralization, the scale of economy should also be considered for future UWI. The choice of plant capacity and treatment technologies depends on multiple factors which might not necessarily be feasible to qualify or quantify. The trade-offs between governance aspects, redistribution costs, recycling opportunities, life-cycle costs and resilience between highly centralized and highly decentralized systems are highlighted in this work. Although it is not possible to establish a perfect number for scaled decentralization in a given context, the approach of moving towards the optimal zone combining centralized and decentralized treatment systems is the take-away message of this study. Lastly, the study emphasizes that the overall UWI strategy is more important than the actual technological choices and presents a perspective that technologies for decentralization can be both high-tech or low-tech and depends on the site conditions and scale of implementation. We hope that this study reaches the appropriate target audience of researchers, practitioners and urban local bodies who will implement the learnings and further contribute to quantifying the economic scale of decentralization through optimization models, case studies and policy changes.

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Statements and Declarations

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Ethical Responsibilities of Authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.