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Need to adopt scaled decentralized systems in the water infrastructure to achieve sustainability and build resilience

Pradip P. Kalbar[a,b,c,*] and Shweta Lokhande[a]

[a] Centre for Urban Science and Engineering (CUSE), Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400 076, India
[b] Interdisciplinary Programme in Climate Studies, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400 076, India
[c] Ashank Desai Centre for Policy Studies, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400 076, India
*Corresponding author. E-mail: kalbar@iitb.ac.in

PPK, 0000-0002-1436-3609

ABSTRACT

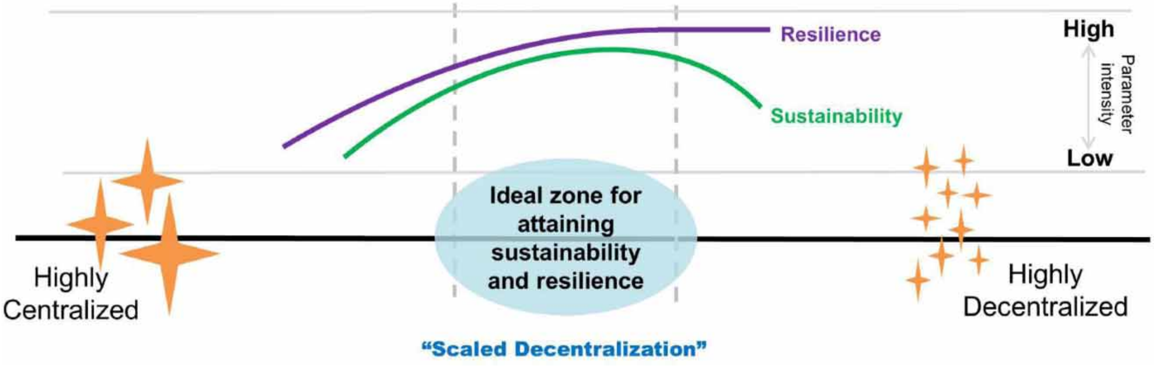
Urban water infrastructure (UWI) in cities faces enormous pressure to cope with increased water demands, handle extreme events and improve the service with minimum resource consumption and environmental impacts. The current study presents an approach for addressing the challenges in UWI, specifically in water supply and sewerage. 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. Furthermore, 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 ageing UWI to create future sustainable and resilient urban systems

Key words: Decentralization, Resilience, Scale of decentralization, Sustainability, Urban water systems, Water and wastewater infrastructure

HIGHLIGHTS

- Problems prevailing in the current infrastructure planning are documented.
- Sustainability and resilience aspects need to be considered in the planning of urban water infrastructure.
- Drivers for decentralized water and wastewater infrastructure are identified.
- The concept of scaled decentralized systems is proposed in water infrastructure.
- Scaled decentralization will create future sustainable urban systems.

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 & 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. The lack of adequate infrastructure creates hurdles to 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, two out of three 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 & Lee, 2019).

1.1. Need for both sustainability and resilience perspectives

The prevalent urban water cycle is dominantly linear since the 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 & Kalbar, 2020; Kalbar, 2021). Additionally, the resilience of urban water infrastructure (UWI) has also become the focus of discussion recently (Lawson *et al.*, 2020). 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. Furthermore, 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). Additionally, in recent times, climate change has emerged as a challenge of this century; hence, the other important aspect of 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, 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. In this context, UWI needs to fulfil 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 the varying service levels expected during emergencies.

A conceptual framework has been proposed by Zhang & Li (2018) to capture the differences between urban resilience and urban sustainability. While sustainable systems cannot necessarily be resilient and *vice versa*, it is important for the UWI to fulfil the expectations of both these aspects. However, hardly any studies have approached UWI planning that simultaneously addresses both sustainability and resilience.

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 the centralized planning of UWI and proposes a shift towards decentralization for achieving the Sustainable Development Goals (SDGs) and mitigating climate change. Furthermore, the article identifies various drivers of decentralization to develop an understanding of decentralized water infrastructure's ability to simultaneously achieve sustainability and build resilience. 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. With this background, the objectives of the study are:

1. To identify the lacunae in current urban water management
2. To identify the drivers for decentralized UWI
3. To introduce the concept of scaled decentralization in UWI and highlight its significance to achieve sustainability and build resilience

2. WHAT IS WRONG WITH THE CURRENT UWI

The current UWI is mainly focused on a centralized approach to infrastructure creation. Historically, such an approach had evolved to provide clean drinking water and maintain hygienic conditions in emerging cities in the early 1900s (Luby *et al.*, 2020). During that time, the cities and urbanization scales were not of the scale in current times. The centralized approach has commonly been adopted without thinking about the needs of 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 & Stenstrom, 2009; Kalbar *et al.*, 2012b).

The disadvantages of centralized UWI are now evident (Libralato *et al.*, 2012; Eggimann *et al.*, 2015; Jung *et al.*, 2018). 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, '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 the 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 3,220 million litre per day (MLD) water from outside its boundary, ranked third in the list of the 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 the government allots funds based on the current population, whereas the treatment plants are designed for the future population forecasted. Additionally, centralized treatment systems are more vulnerable to extreme events and a 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 leakage losses are estimated to be around 20%, whereas in some cases, it escalates to more than 50% of distributed freshwater (Haghighi & 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 increase 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 & 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, the multi-outlet tank usage demonstrated by Ghorpade *et al.* (2021a) will help in the formation of district-metered areas without numerous valve operations and achieve 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). Furthermore, to tackle sanitation issues, the provision of toilets is focused on, 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 phases (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 the 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.*, 2023). Although centralized infrastructure helps achieve a greater scale of economy in treatment, it tends to 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 the 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 the usage of safety devices during sewage disposal, a 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 is typically abstracted by cities located at the downstream end or used for irrigation purposes, which can again 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 the unbundling of services as an opportunity to improve operational efficiency by introducing the private sector (Parkinson & 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 a 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, the use of aerators in mechanized treatment systems consumes around 75% of energy during biological treatment (Kalbar *et al.*, 2012a; Maktabifard, 2018). 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 decentralized-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 & Kalbar, 2020).

2.3. Lack of a holistic approach for planning UWI

The present approach to water provisioning in cities and its implications on the environment is depicted in Figure 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 and global impacts (Arcas-Pilz *et al.*, 2021). Furthermore, 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 the atmosphere due to agricultural activities and synthetic detergent usage are causing nitrate pollution, eutrophication and greenhouse gas emissions, respectively, and eventually disturb 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 Figure 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. Furthermore, 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 such as 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 for recovering energy and struvite precipitation for recovering phosphorus have been implemented at different scales in the urban settings. The use of by-product

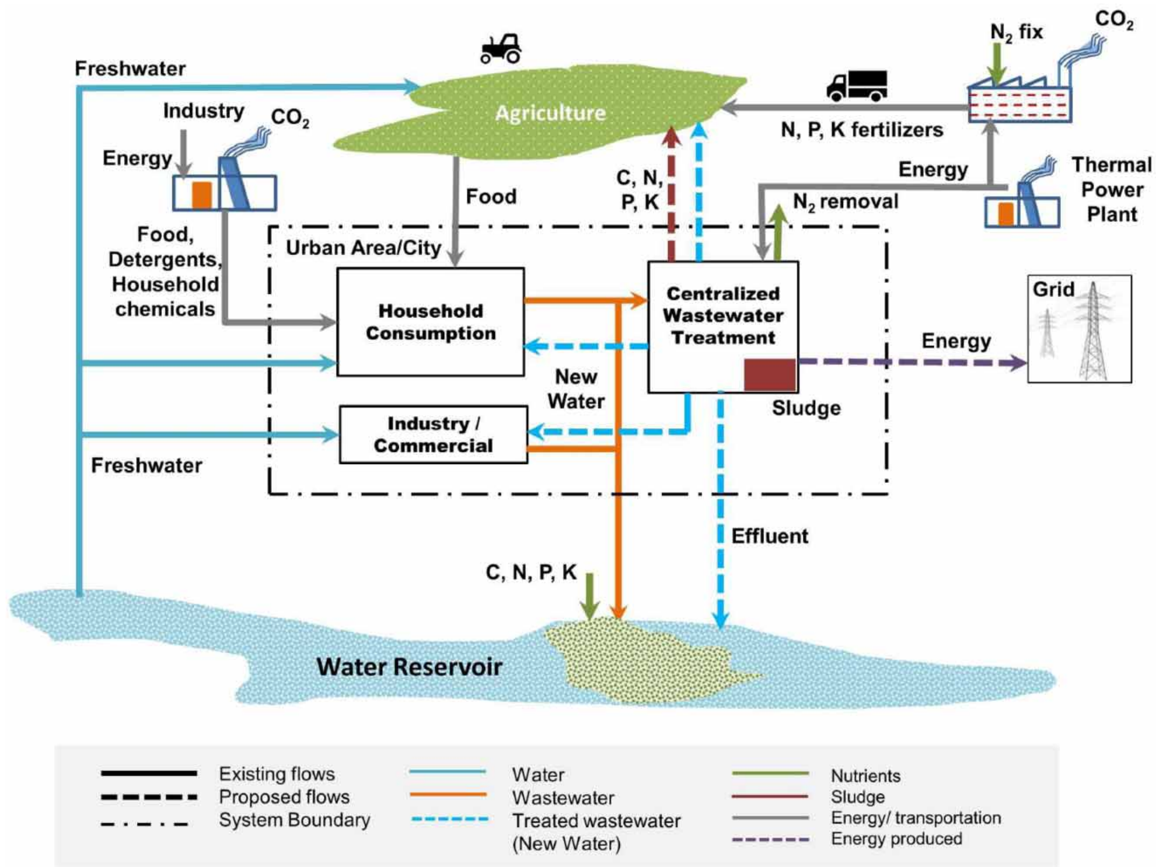


Fig. 1 | Energy and nutrient flows in a centralized urban wastewater system and envisaged changes.

sludge can become valuable in agriculture. Furthermore, 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). Analysis of historical data has proved the deteriorating water quality of rivers to be associated with increasing urbanization taking place in cities lying on the banks of rivers (Lokhande & Tare, 2021). 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 of 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 favourite 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 the 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 1,631 STPs (planned and installed) with a total capacity of 36,668 MLD, only 1,093 STPs are operational treating approximately 73% of sewage, i.e., 26,869 MLD of sewage (CPCB, 2021). On the contrary, well-planned and phase-wise infrastructure development will completely utilize the infrastructure and reduce 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 sub-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). Furthermore, 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, evaluation of policy initiatives and governing institutions (Kalbar *et al.*, 2016; Rathnayaka *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 Table 1.

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 & Lee, 2019). Resilience has been associated with characteristics such as robustness, rapidity or

Table 1 | Sustainability aspects of decentralized UWI

Driver	Description
Economic benefits	• Improved pressure in water supply networks • Energy savings due to the phased and modular development of infrastructure • Easy operation of sewerage systems owing to less depth of excavation • Decentralized systems prove economical over the long operational life of the UWI • Create opportunity to adopt nature-based solutions for wastewater treatment
Social benefits	• Equitable water distribution can be achieved in the tail-end of cities • Utilization of local labour and women can generate employment • Delegating O&M authority to community may imbibe a sense of ownership that sustains STPs • Modular designs of decentralized treatment units are 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 the 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, recognized as resource carriers amidst the energy-intensive production of nitrogen fertilizers and the depleting reserves of phosphorus rock, can be recovered in decentralized systems • 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, and biodiesel
Environmental impacts	• Reduced operational energy in the decentralized UWI results in reduced greenhouse gas (GHG) emissions • Opportunity to create circular economy at the local scale and closing the nutrient loops resulting in better water quality • Full capacity utilization happens in decentralized systems reducing unnecessary wastage of resources
Ease of governance	• The installation of decentralized systems involves less complexity due to lesser number of institutions involved • The tendency of delays in large infrastructure projects due to land acquisition and tendering is avoided in decentralized systems

recovery, redundancy, reliability and buffering. The concept of resilience has multidisciplinary origins, which 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 the one that 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). Furthermore, 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 minimal 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.

4. SCALED DECENTRALIZED UWI

Decentralized UWI is beneficial in multiple ways for all the stakeholders, as such systems 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 socio-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 construction and operation. However, there are no further benefits associated with scaling up after achieving a particular scale in a given system. Also, the management-related challenges of smaller decentralized infrastructure increase with the number of small systems, subsequently escalating the maintenance cost in proportion. For example, Kigali city completely failed in handling onsite sanitation systems at the individual and collective levels (Kazora & 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 the economy or attain the water quality standards and, 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

Table 2 | Resilience aspects of the decentralized UWI

Driver	Description
Robustness	• Decentralized systems are less vulnerable to extreme weather events • Failure of centralized system performance affects the entire region, whereas decentralized systems allow to cater small regions and non-performance of the single system does not affect another, hence more robust approach • Varying hydraulic loads and water quality emerging from future changes can be easily tackled in decentralized systems
Adaptive capacity	• Creating a 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	• Decentralized systems facilitate flexibility by virtue of phasing out the construction of wastewater treatment infrastructure with time • Decentralized systems are easy to retrofit and hence can be modified to achieve newer regulations • The learnings from localized problems can be incorporated while designing the future phases of decentralized STPs

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 the economy are gained. Such a decentralized approach with an optimum scale of operation is essential for the smooth functioning of UWI (Kalbar & Gokhale, 2019). Moreover, climate change, population expansion and ageing 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.

The distinction between centralized and decentralized treatment systems is depicted in Figure 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. Furthermore, 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. Recently, Sood *et al.* (2023) have comprehensively documented the advantages and disadvantages of centralized and decentralized water systems.

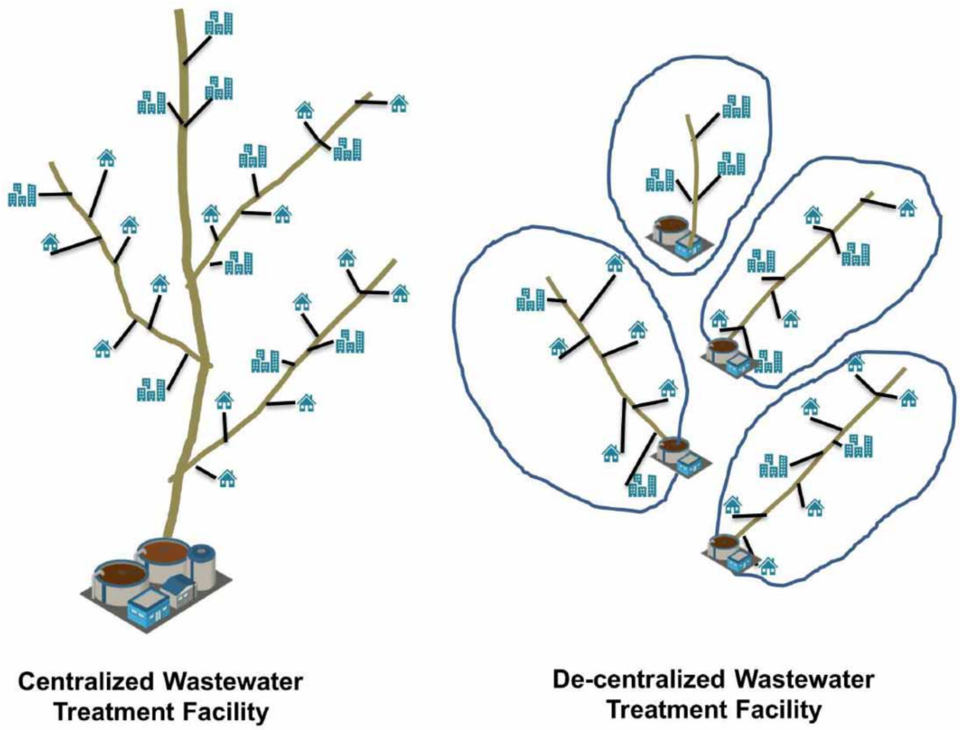


Fig. 2 | Centralized and decentralized infrastructures.

4.1. Trade-offs between centralized and decentralized UWI

The trade-offs between adopting a highly centralized or highly decentralized UWI are depicted in Figure 3, where the effects of these systems on sustainability and resilience are notionally depicted. The *x*-axis denotes the scale of decentralization, for example, city level or community level or household level. The *y*-axis denotes the parameter representative of drivers that are normalized on a scale of low to high. The sustainability aspect is discussed through six parameters, namely life-cycle costs, the potential for recycling water, resource recovery, social benefits, environmental impacts and ease of governance, while the resilience aspect is indicated through three parameters, namely robustness, adaptive capacity and flexibility. Based on the discussion on drivers for decentralization in Section 3, this section summarizes the notional trends of all parameters for sustainability and resilience based on the author's understanding of UWI.

With respect to **sustainability**, the *life-cycle cost* (comprising both capital and O&M costs) of highly centralized systems tends to be higher and it reduces towards decentralization (Tjandraatmadja *et al*., 2005) up to a certain point beyond which the treatment cost increases due to an increased number of STPs. The *social benefits* in terms of community involvement, women participation and local labour employment are higher in decentralized systems (Lekshmi *et al*., 2020). Decentralization provides greater opportunities for a *market for recycled water* and further reducing the redistribution cost (Kobayashi *et al*., 2020). Hence, the potential for recycling water is higher for decentralized UWI and is more economical as compared to centralized systems (Kavvada *et al*., 2018). Furthermore, decentralized systems favour a higher *resource recovery* ratio due to the ease of source separation. Also, the resource recovery is economically viable at a larger level than at household levels (Libralato *et al*., 2012). Coupling the scale and source separation aspects, resource recovery is the highest for an appropriate scale of implementation. Considering the *environmental impacts* of wastewater treatment, centralized systems tend to consume more energy and hence emit more greenhouse gas emissions (Kavvada *et al*., 2016). The

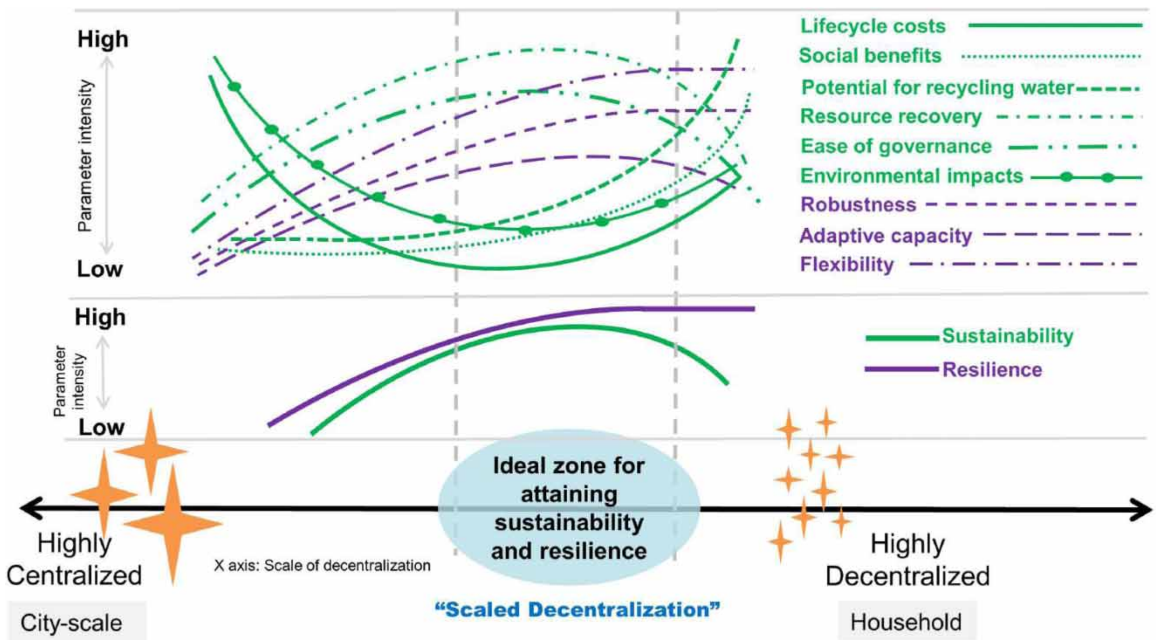


Fig. 3 | Ideal zone of UWI for achieving sustainability and resilience based on various parameters.

environmental impacts reduce towards decentralized systems up to a certain point, beyond which a greater quantity of materials and resources consumed in treatment systems are associated with greater embodied emissions. Furthermore, the coordination among the service providers is better managed in decentralized systems operating at a community scale as against individual households. The O&M of small-sized infrastructure systems is relatively easy. Also, the complexity involved in outsourcing infrastructure projects increases for highly centralized systems and causes inconvenience in implementation, for example, delays due to tendering, land acquisition, involvement of multiple agencies, etc. Coupling the above trends, it is observed that the ease of governance is on the lower side for centralized systems, increasing towards decentralization up to a point, beyond which it further reduces.

As far as **resilience** is concerned, decentralized systems function well amidst changing environments and can resume service in less time than centralized systems. Centralized systems are less robust and more vulnerable to failures. For example, water supply systems use natural water bodies as their source, which might be at greater risk of flood or drought or any other case of water contamination (Liu *et al.*, 2021). Decentralized systems can have multiple or localized water sources, for example, reclaimed water for non-potable purposes thus increasing their resilience. Hence, the *robustness* of centralized systems is the lowest and it increases towards decentralization. With regard to adaptive capacity, the time within which service can be provided after failure is crucial. This can be easily achieved for decentralized systems of smaller capacity, which can be installed in a few days or months as against large centralized systems that may take even years to get commissioned. Also, moderate investments are suggested to achieve increased recoverability, which also result in enhanced robustness (Liu *et al.*, 2021). Additionally, the organizational aspect of resilience plays a key role in implementation. Decision-making during a crisis can be better achieved at the community level than individual households, while it may get prolonged in highly centralized projects. Thus, *adaptive capacity* increases towards decentralization up to a certain point, beyond which it decreases slightly. Furthermore, the need for large systems is suggested for increased resilience; however, a large capacity of such large systems remains idle in the initial years resulting in capital costs being futile. In this background, reducing investments by building infrastructure that provides service for only 10 years is suggested instead of planning the service provision for 50 years (Giordano, 2012). Implementing decentralized systems in a phase-wise manner proves to be cheaper, more efficient and also capable of responding to new developments occurring in the area, earning higher flexibility. Thus, the decentralized UWI provides greater *flexibility* than their centralized counterparts and hence is depicted by an increasing trend in Figure 3.

To holistically plan and implement UWI, the culmination of all the above parameters is needed. Hence, the notional trends of these parameters are collectively shown in Figure 3. In an ideal UWI, the sustainability and resilience of UWI should be the maximum, which can be only possible through the appropriate level of decentralization. As Figure 3 depicts, the resilience of UWI increases towards decentralized systems and stabilizes after one size or scale, whereas sustainability decreases beyond one point. It is observed that the most economical systems having maximum benefits tend to fall between the highly centralized and highly decentralized systems. Consequently, the mid-zone becomes most favourable 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, neighbourhood and household scales that have 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 neighbourhood scale is suggested as a potential reuse scheme (Makropoulos *et al.*, 2018).

4.2. The concept of scaled decentralization

Decentralized systems are often considered equivalent to onsite treatment systems. Furthermore, 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, either onsite or natural treatment systems cannot be solely categorized as decentralized solutions. Decentralized systems can operate at different spatial scales, namely, 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 onsite 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, and the guiding principle for scaling semi-centralized systems is 'as small as possible as big as necessary' (Böhm *et al.*, 2011). In our study, the water supply or wastewater collection and treatment systems designed for a discretely selected population size to achieve the scale of the economy that can maximize sustainability and resilience at a given location are referred to as '*scaled decentralized systems*' (SDSs). SDSs should be designed considering population density, land availability, regulations, stakeholder interests and fund availability with the Urban Local Body (ULB). SDS has 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 SDS to achieve sustainable and resilient UWI.

Planning urban water supply involves decision aspects such as the location of elevated storage reservoirs, the sizing of networks and deciding appropriate zones. Similarly, planning water reuse involves numerous decisions, for example, location, size, treatment technology, sewer size and appropriate end-use. Several trade-offs are involved in the decision of deciding the scale of implementing decentralized infrastructure. 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 present study proposes using the size of cities to determine the scale of decentralization for UWI. Based on the author's experience and discussion with experts, a scale of decentralization is suggested depending on the size of the city and the estimated sewage generation. For example, as illustrated in Figure 4, small cities can be regarded as those generating approximately

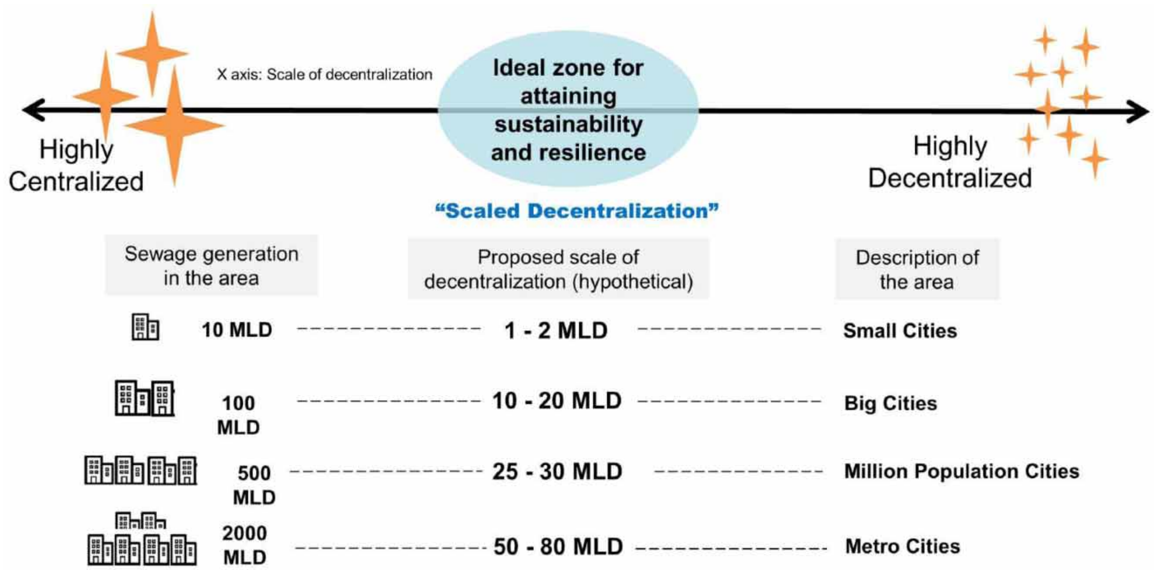


Fig. 4 | Scaled decentralized UWI for different sizes of cities.

10 MLD of sewage as against a metro city generating sewage around or exceeding 2,000 MLD. The authors propose the scale of decentralization to range from 1 to 2 MLD STP for small cities, whereas it can go up to as high as 50–80 MLD for metro cities. A centralized scale for a smaller city can be a decentralized scale for a metro city. 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.

Unless such an appropriately scaled decentralization is adopted, equitable pressure distribution in water supply systems and cost-efficient sewage treatment cannot be achieved. Also, 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 and 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.

4.3. Lack of studies on scaled 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 analysing the cost of wastewater management systems across the varied extent of decentralization (Eggimann *et al.*, 2015; Jung *et al.*, 2018; Sood *et al.*, 2023). 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, the study by Paul *et al.* (2019) shows decentralized treatment systems to have two–three 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. On these lines, Sood *et al.* (2023) have compared the costs of centralized and decentralized sewerage systems for the city of Ludhiana in India and have found the capital costs to be almost comparable. However, there are no such studies available for different alternatives of scaling, 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, the authors propose that for every city, the decentralization scale can be decided based on the scale of the city.

A number of technology options are prevalent for planning the water supply and wastewater systems in a decentralized manner that may include mechanized or nature-based solutions and low-cost or high-tech advanced treatment technologies. 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 laboratory or other field conditions. Hence, the decision regarding technology selection should be done on a case-by-case basis, depending on the scale of implementing the UWI.

Several researchers have pointed out the benefits of decentralization in UWI. Additionally, the present study has systematically discussed the significance of decentralized systems through various drivers from the perspectives of sustainability and resilience. The variation of drivers across the scale of decentralization is illustrated through notional trends, which has led to the definition of SDS, an approach that is a prominent contribution to the existing literature. However, the study is based on a theoretical understanding emerging from the literature review. This work can be regarded as a starting point in the discussion of SDS. Researchers can take up individual drivers and quantify their variation across the scale of decentralization. Also, this quantification can be done for different classes of cities, which can prove the hypothesized optimal scales proposed in Figure 4 through computational analysis.

5. CONCLUSION

The evolution of water infrastructure historically has been 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 the 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 from the perspectives of sustainability and resilience. The present work argues that along with an emphasis on decentralization, there is a need for considering the appropriate scale of implementation in decentralized UWI. 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 difficult 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 the 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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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.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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