Economic Assessment of Centralized and Decentralized Sewerage Network Systems: A Case Study of Ludhiana, India

Bhavnidhi Sood[1]; Shweta Lokhande[2]; Malini Krishnankutty[3]; and Pradip P. Kalbar, M.ASCE[4]

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Abstract: Most of the Indian cities that follow a centralized model of sewerage systems are facing several challenges in its effective implementation and operation. Decentralized systems are identified as a viable alternative to centralized sewerage systems in various studies, mainly because of their water recycling prospects and building resilience. However, there is a lack of studies that compare centralized and decentralized sewerage networks considering real-life data. To bridge this gap, the present study considers Ludhiana, India, for conducting a detailed economic comparison based on the network's capital costs for both systems. The decentralized systems show almost similar capital costs as the centralized system in this study. Hence, both systems can be adopted based on capital cost. However, the study shows that decentralized systems offer more water recycling opportunities, making them preferable to centralized systems. The study also emphasizes that the choice of sewerage systems should be context-specific to fetch maximum economic and environmental benefits.
DOI: 10.1061/JUPDDM.UPENG-4095. *© 2023 American Society of Civil Engineers.*

Author keywords: Wastewater management; Sewerage system; Centralized network; Decentralized network; Economic assessment.

Introduction

As urbanization is taking place globally, it has been observed that 55% of the world's total population lived in urban areas in 2018, and it is expected to reach 68% by 2050 (UN-DESA 2018). Urbanization, along with other factors such as population growth, industrialization, change in land-use patterns, and poor water management, imposes enormous pressure on water resources. Around the globe, 40% of the population is already facing water scarcity and water stress, and the ratio of freshwater withdrawn to available renewable freshwater resources is expected to worsen in the future. Central and southern Asia and Northern Africa fall under high water stress zones with a stress level as high as 70% (UN 2020). Because water is a renewable resource and an essential element for human survival on earth, it needs to be adequately managed, indicating the need for efficient wastewater management. The sixth goal among the 17 sustainable development goals of the United Nations, to be achieved by 2030, is, "Ensure availability and sustainable management of water and sanitation for all" (UN 2020). However, in the current scenario, only 20% of the globally generated wastewater is being treated, while the remaining 80% enters untreated water bodies (UN-WATER 2015). The situation is no different in India, where only 28% of the total wastewater generated in Indian cities is being adequately treated (CPCB 2021). The rest is directly discharged into water bodies, contaminating the surface and groundwater across the country.

Domestic sewage, also referred to as "wastewater" in this paper, needs to be considered a resource to maintain the water budget, and effective wastewater management strategies must be implemented. The circular economy is one such concept being explored by researchers for implementing sustainable wastewater management strategies, such as the 6Rs (Reduce, Reuse, Recycle, Recover, Reclamation, and Restoration) in urban areas (Kakwani and Kalbar 2020). Historically, to prevent the outbreak of waterborne diseases, the conventional approach of centralized systems that transported domestic sewage to a remotely located sewage treatment plant emerged in cities (Luby et al. 2020). However, as the cities experienced rapid outgrowth and the density of settlements became sparse in the urban peripheral areas, the economic viability of these systems was observed to reduce (Hophmayer-Tokich 2006). Even in Indian cities, the success of conventional sewerage systems is hindered due to the financial incapacity of the urban local bodies to maintain the sewerage systems, high resource inefficiency, remote locations of sewage treatment plants (STPs), and high investment and operation and maintenance (O&M) costs (CPHEEO 2013). Decentralized sewerage systems treating wastewater close to the point of generation, on the other hand, are being recognized as a viable alternative to the conventional centralized systems in terms of environmental favorability and the potential for water reuse (Jung et al. 2018; Libralato et al. 2012). However, the economic viability of these systems needs to be assessed as economic criteria mainly govern the choice of sewerage infrastructure.

Wastewater management includes wastewater generation, transportation, and treatment processes, out of which the collection and treatment systems are cost-intensive in terms of their capital and O&M costs. Most of the existing research is focused on analyzing the treatment aspects of centralized and decentralized sewerage systems, whereas the collection network lacks intensive research. Economic evaluation is one of the essential criteria for the sustainability assessment of urban water and wastewater systems (Hellström et al. 2000). However, the cost of sewer systems, an

[1]M.Tech. Student, Centre for Urban Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India. Email: bhavnidhi96@gmail.com

[2]Prime Minister's Research Fellow, Centre for Urban Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India. Email: 204420002@iitb.ac.in

[3]Adjunct Associate Professor, Centre for Urban Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India. Email: malini.kutty@iitb.ac.in

[4]Associate Professor, Centre for Urban Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India (corresponding author). ORCID: https://orcid.org/0000-0002-1436-3609. Email: kalbar@iitb.ac.in

Note. This manuscript was submitted on March 8, 2022; approved on January 23, 2023; published online on April 18, 2023. Discussion period open until September 18, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Urban Planning and Development***, © ASCE, ISSN 0733-9488.

essential component of cost analysis, is often excluded during their economic evaluation. Roux et al. (2011) reported in their study that the sewer network has a considerable contribution to make to the overall environmental footprint of the sanitation system and also emphasized the need to assess the economic impact of sewer networks. In a conventional sewerage system, the collection network carries a significant economic burden with a high share, of about 80%, in the overall capital costs of the system (Libralato et al. 2012; Arceivala and Asolekar 2008). Nawrot et al. (2018) have indicated in their study that there is an opportunity to optimize the cost of collection systems by adequate selection and sizing of its inventory.

As the attention is being shifted toward the overall optimization of urban sewerage systems, it necessitates finding costs for the collection systems at various scales of centralization (or decentralization) for achieving a better comparison.

Need for a Comparative Assessment of Centralized and Decentralized Sewerage Systems

An Indian city is either typically dependent on on-site systems or is partially/fully covered by the underground sewer network/open-drain network for wastewater management. It has been reported that in 2021, the total installed sewage treatment capacity of STPs in the urban centers of India was just 44% of the total sewage generation (CPCB 2021). Furthermore, only 64% of the installed sewage treatment capacities are utilized, indicating the inadequacies in the sewage collection and sewage treatment facilities in Indian cities. As urban development is proceeding at a fast pace, there is a need to serve these cities with fully laid out sewerage systems to overcome problems related to sanitation. However, achieving 100% sewerage systems is not practically feasible. Against this background, adopting decentralized systems along with a centralized sewer network proves beneficial. A comparative economic assessment of centralized and decentralized systems may help in making informed choices while designing urban sewerage systems, and such studies have been carried out by Woods et al. (2013), Eggimann et al. (2015), Jung et al. (2018), and so on. However, there is no consensus among these studies; hence, there is a need for increased research advocating for the need to frame revised design guidelines in this regard.

Eggimann et al. (2015) have performed a study based on modeling the optimal degree of centralization for sewerage systems with a focus on cost minimization using a planning tool based on the shortest pathfinding approach and clustering algorithms. The study found that the optimal degree of centralization decreased with increasing topographical complexities and dispersed or less dense settlements. Also, such a model is difficult to implement on the ground since sewer network design depends on various dynamic processes and variables such as population trends and settlement patterns. Hence, such an approach requires a more context-specific understanding, thus making this kind of data-dependent model challenging to implement in developing nations such as India due to data insufficiency and the organic growth of urban centers.

In their study, Jung et al. (2018) focused on a cost comparison between centralized and decentralized sewerage systems. The centralized system was designed for the Alibaug region in India according to the Central Public Health and Environmental Engineering Organization (CPHEEO)'s Manual on sewerage and sewage treatment systems. For the decentralized systems, a three-step simulation model was used for testing various configurations and cluster layouts of sewerage systems. The simulations included randomized STP allocation, cluster formation using sewer path optimization, and a simplified sewer design, which was followed by cost calculation in terms of current values. The results showed that the large-clustered decentralized models had relatively low O&M costs but a higher capital cost and land requirement when compared with the centralized system (Jung et al. 2018). However, such a modeling approach does not consider the ground complexities in urban areas that include physical constraints such as topographical variations, high water tables, and rocky soil conditions and sociopolitical constraints. Comparative assessments need to consider the ground reality and local context for analyzing decentralized models in research studies to obtain more accurate results.

Hence, the present study aims to evaluate the economic feasibility of a decentralized sewerage system as a potential alternative to the conventional centralized sewerage system in urban areas, focusing on water reuse opportunities. The study also generates outputs and learnings for other cities facing similar issues related to centralized sewerage systems. A large Indian city with a population exceeding 1 million has been considered for understanding the ground issues in the sewerage systems at the urban level and conducting further studies.

Comparison of Centralized and Decentralized Sewerage Systems

Centralized sewerage systems are the conventional means of sewage collection and transport. The entire area's wastewater is transported mostly via gravity flow to a remotely located sewage treatment unit in such a system. Various factors, such as population projections and growing per capita water needs, are also considered while designing centralized systems (Bernal and Restrepo 2012). The concept of using a fully networked sewerage system comes from the United States and Europe, where this system was first introduced to cater to the increasing wastewater loads due to urbanization as well as to lower the incidences of diseases arising out of unhygienic conditions and direct exposure to waste (Burian et al. 2000; Hophmayer-Tokich 2006).

Decentralized sewerage systems involve the collection, transportation, treatment, and disposal or reuse of wastewater at or near the point of waste generation (CPHEEO 2013). On-site treatment systems with the treatment unit located within the site of wastewater generation itself are commonly known as decentralized treatment systems. This system is a historical method of wastewater management practiced even before the introduction of centralized systems in many geographies across the globe (Burian et al. 2000; Hophmayer-Tokich 2006). However, multiple sewage treatment plants implemented at varying scales and catering to a part of the population load of a city or town are also known as decentralized treatment systems. Of late, decentralized systems are becoming popular as a possible alternative to conventional centralized sewerage systems. Many researchers are exploring the novel approach of optimizing the decentralization scale that can fetch the maximum benefits from the decentralized sewerage systems (Eggimann et al. 2015; Jung et al. 2018). Such a scaled approach for decentralization can overcome the limitations of centralized and decentralized systems and provide higher sustainability and resilience to the infrastructure.

Centralized Systems—Advantages and Disadvantages

Centralized systems have continued to be in use for several years due to many reasons, but it has been realized lately that the O&M costs of these systems are high (Jung et al. 2018). Additionally, the process of renewing or upgrading the collection system

J. Urban Plann. Dev., 2023, 149(3): 05023016

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

after it reaches its end-of-life stage is economically burdensome and tedious (Barron et al. 2017).

The limited availability of financial resources in many urban areas, especially in developing nations, makes centralized systems the first choice among engineers (Singh et al. 2015). Furthermore, the easiness of planning and implementing large-scale centralized treatment systems is another reason for its popularity among engineers. This also fits well with the political goals of the politicians of the day to announce large investments in treatment infrastructure.

Amidst the scenario of scarce land in the core city, centralized treatment plants are usually located on a single large piece of land away from the main urban center. This also addresses the social unacceptance of the provision of a treatment unit in the residential vicinity. However, the control of the treatment systems and their O&M is affected due to limited accessibility, given its isolated location (Bernal and Restrepo 2012).

When accounting for wastewater quality in centralized systems, there is nonuniformity in the composition as the wastewater is received from different sources (Bernal and Restrepo 2012). This may become a burden on the treatment unit to maintain sewage disposal standards. Additionally, the redistribution of treated wastewater back to the city becomes highly uneconomical as it is concentrated at a single point away from the city, resulting in a low water reuse potential (Arceivala and Asolekar 2008; Ho and Anda 2006).

The concept of a centralized system has been derived from developed nations, where there is high water consumption and adequate flushing velocity, which does not allow siltation or choking in sewers. However, this concept is not necessarily suitable in the context of developing countries having low and intermittent water supply, causing the problem of sedimentation in sewers (CPHEEO 2013; Sitzenfrei and Rauch 2014). The developing nations undergo uncontrolled urbanization resulting in the growth of unplanned settlements with nonuniform densities. Adopting centralized systems for conveying the wastewater to larger distances escalates the network costs in such conditions. Additionally, centralized treatment systems are highly dependent on power supply for their operation, and the availability of electricity for their smooth functioning can be influenced by any economic or political policy issues (Bakir 2001; Libralato et al. 2012). The urban characteristics of settlements, such as population density, land topography, building density, and land occupation, determine the favorability of centralized networks (Roux et al. 2011). These systems can work well for the developed and densely populated areas of any settlement, for instance, residential and commercial centers or densely packed core areas.

Decentralized Systems—Advantages and Disadvantages

The decentralized models provide effective solutions for wastewater management in smaller communities and periurban settlements. They require a relatively low budget and also provide opportunities for water reuse without excessive expenditure on water supply infrastructure (Bakir 2001; Massoud et al. 2009; Nanninga et al. 2012; Wang 2014). Factors such as large elevation differences, inadequate existing capacities, demand at the periphery, and lower discount rates favor this system (Woods et al. 2013). When targeting water reuse prospects from decentralized systems, it becomes essential to consider the location, system size, sewer size, degree of decentralization, applications of recycled water, treatment standards, and public acceptance (Jung et al. 2018; Woods et al. 2013). Water reuse opportunities can be seen in landscape and agriculture (parks, gardens, green belts, crops, etc.), environment (surface water bodies), nonpotable urban uses (toilet flushing, washing, firefighting, etc.), and nonpotable industrial uses (Arceivala and Asolekar 2008).

Decentralized systems can also be advantageous because the design period can be kept shorter for smaller investments in phases (Jung et al. 2018). This may even cater to uncertain and dynamic factors such as population growth and changing land-use patterns. The capital costs for sewage treatment units in decentralized systems are higher when compared with those in centralized systems. However, the sewer capital costs and the O&M costs are much lower for decentralized systems (Jung et al. 2018) owing to the reduced pipe lengths and manhole sizes that are laid at a shallow level under the ground. Also, since the wastewater quantities generated are relatively small, there is a possibility of using natural and nonmechanized sewage treatment technologies such as ponds, constructed wetlands, and so on. These systems can further lower the O&M costs as they do not require power and are easy to operate and maintain (Arceivala and Asolekar 2008; Kamal et al. 2008). The land requirement for decentralized systems is much higher or sometimes even twice (Jung et al. 2018) than the land requirement in centralized systems. Due to odor and noise issues, the public acceptance toward setting up sewage treatment units in the vicinity of residential areas does not present a very optimistic picture.

The effective execution of decentralized systems faces governance challenges such as generating revenue for operating an increased number of STPs, ensuring the compliance of effluents with guidelines, and so on. As decentralized systems are gaining in popularity, private service providers have emerged to implement decentralized technologies. However, most of the systems being implemented in India do not comply with effluent standards due to a lack of suitable governance provisions (Reymond et al. 2020). Further, there is a shortage of incentives and budget allocation for improving urban sanitation services for the poor, making it challenging to provide on-site systems. A holistic approach wherein government agencies proactively participate to ensure effective enforcement has to be adopted. Active participation by various stakeholders, including government agencies, local bodies, and the end customer, is required for better decision-making and infrastructure development at household levels (Putri 2017). Hence, decisions such as location for STPs and technology selection should be taken by urban local bodies after consultation with relevant stakeholders. This will ensure the sustenance of the sewerage infrastructure.

Table 1 briefly compares the centralized and decentralized systems based on economic, social, environmental, technical, governance, and urban settlement characteristics. An elaborated version of the same is presented in Table S1 in SI. In summary, decentralized systems might not be preferable over a centralized system in areas with high population density and an already existing sewer system. Therefore, adopting both systems at different locations as per site-specific conditions could be a better choice rather than preferring one over the other.

Methodology

The methodology adopted for conducting the study is depicted in a flowchart in Fig. 1. The objective of this research is a cost-based comparison of sewerage network systems, which included identifying the types of sewerage systems and their inventories for the cost comparison.

Three types of sewerage systems were considered for the study based on their scale of implementation, i.e., centralized and decentralized, and neighborhood networks, each catering to a part population load. Sewer pipes and manholes were the two main network

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Table 1. Comparison of centralized and decentralized sewerage systems

Parameter	Centralized systems	Decentralized systems
Economic		
Collection system cost	Around 80% share in total cost	Low cost of collection system
Treatment plant cost	Smaller share in overall system cost	Higher share in overall system cost
Capital cost	Less in comparison with decentralized	Higher as compared with centralized
O&M cost	Higher O&M and replacement costs due to longer life span	Lower O&M and per-capita replacement costs due to a shorter design period
Social		
Public acceptance	Well-accepted; established guidelines	Lack of public acceptance due to odor
Health impacts	Better public health; no direct exposure	Appropriate technologies can facilitate better public health
Environmental		
Water reuse potential	Limited scope for recycling	Increased recycling opportunities
Land requirement	Large; away from urban centers	Smaller land parcels in the nearby vicinity
Technical		
Collection system	Larger excavation depths, sizes, and lengths of sewers	Smaller diameter, length, and excavation depths
Innovation in treatment technologies	Lesser opportunities for technological upgradation	Potential for technological innovations due to its shorter design period
O&M effort	Less skilled/high-skilled resources needed	Facilitate semiskilled/ unskilled workforce
System resilience	Failure in the treatment plant affects the complete network	Failure risk lowered due to staggered systems
Wastewater uniformity	Relatively nonuniform composition	Relatively uniform composition
Governance		
Policies/guidelines	Readily available design guidelines	Need for detailed guidelines and policies
Control	Better control due to a single unit	Loss of control due to multiple plants
Urban settlement characteristics		
Population density	Suitable for a high population density	Favorable for scattered peripheral developments having low density
Topography	Work better for a flat or gently sloping topography	Higher elevation differences favor decentralized systems

components considered for the cost calculation in all the sewerage networks. Sewer pipes were further divided based on their size into branch/lateral pipes and trunk/main pipes. The layout for the network was finalized in QGIS software version 3.10.9-A Coruña, and the networks were designed and optimized in Microsoft Excel.

The network design and optimization were performed using data on the existing sewerage system of Ludhiana, India, along with guidelines from the CPHEEO's manual on sewerage and sewage treatment (Part A: Engineering) (CPHEEO 2013). As described in the CPHEEO manual, the sewer design process involved various steps for the estimation of design flows such as population forecasting, design period, tributary area, per capita sewage flow, and infiltration rates. This was then followed by sewer network layout design and network optimization considering the standard specifications provided in the CPHEEO manual. The last step after sewer network design is the cost estimation to obtain the cost comparison results, followed by discussion and conclusions.

Once the sewerage network was designed, costs were calculated in the subsequent step. The capital costs of the sewer pipes and manholes were considered for the cost calculation of all the networks. The total system capital cost calculation included the network cost (pipes and manholes) along with the treatment cost, which was sourced from the literature and field experts. The final step of the study involved an economic comparison of the costs calculated for both networks.

Study Area

Ludhiana, a city in North India, was chosen as the study area for conducting the comparative analysis between centralized and decentralized systems. The city is an industrial hub in the state of Punjab, spread across an area of 159 km^2 with a population of 16 lakhs approximately, and contributes significantly to the state's economic growth. Although this city provides for a suitable business environment, it has been embroiled in various environmental issues due to rapid urbanization and industrialization.

Ludhiana follows a centralized sewerage system model for wastewater collection. The city has been segregated into three sewerage zones according to the areas served by three STPs. The wastewater collected in each zone is conveyed to the three STPs situated at different locations outside the city's Municipal Corporation limits, as shown in Fig. 2.

The sewerage system includes a hierarchical network of lateral pipes connecting to the households, submain sewers, main sewers, and trunk sewers connecting to the STPs. The majority of the sewer connections are residential, followed by commercial connections, and there has been an 80-fold decadal (1994–2006) increase in the number of total sewer connections in the city (CDP 2007; PUDA 2011). However, some parts of the city, mainly the peripheral areas, are devoid of connections to the sewer network and depend on the usage of septic tanks, soak pits, or open drains for disposing the discharged sewage. Also, most parts of the city, including the industrial and residential areas, face frequent sewer choking. The sewer choking can be attributed to several factors, including the discharge of industrial effluents into the sewers, the degraded physical condition of old sewers, ever-growing water demand, lack of regular cleaning, silting due to stormwater disposal in sewers, improper solid waste management, improper design, and incorrect slopes of sewer lines causing a reduction in self-cleaning velocity. Also, the capacities of the sewers are inadequate and overloaded due to stormwater entering the network. In addition, the city does not have many provisions for stormwater drainage. Only 11% of the entire city area is covered by the stormwater network that has not been upgraded or supplemented after 2002 (CDP 2007; PUDA 2011).

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

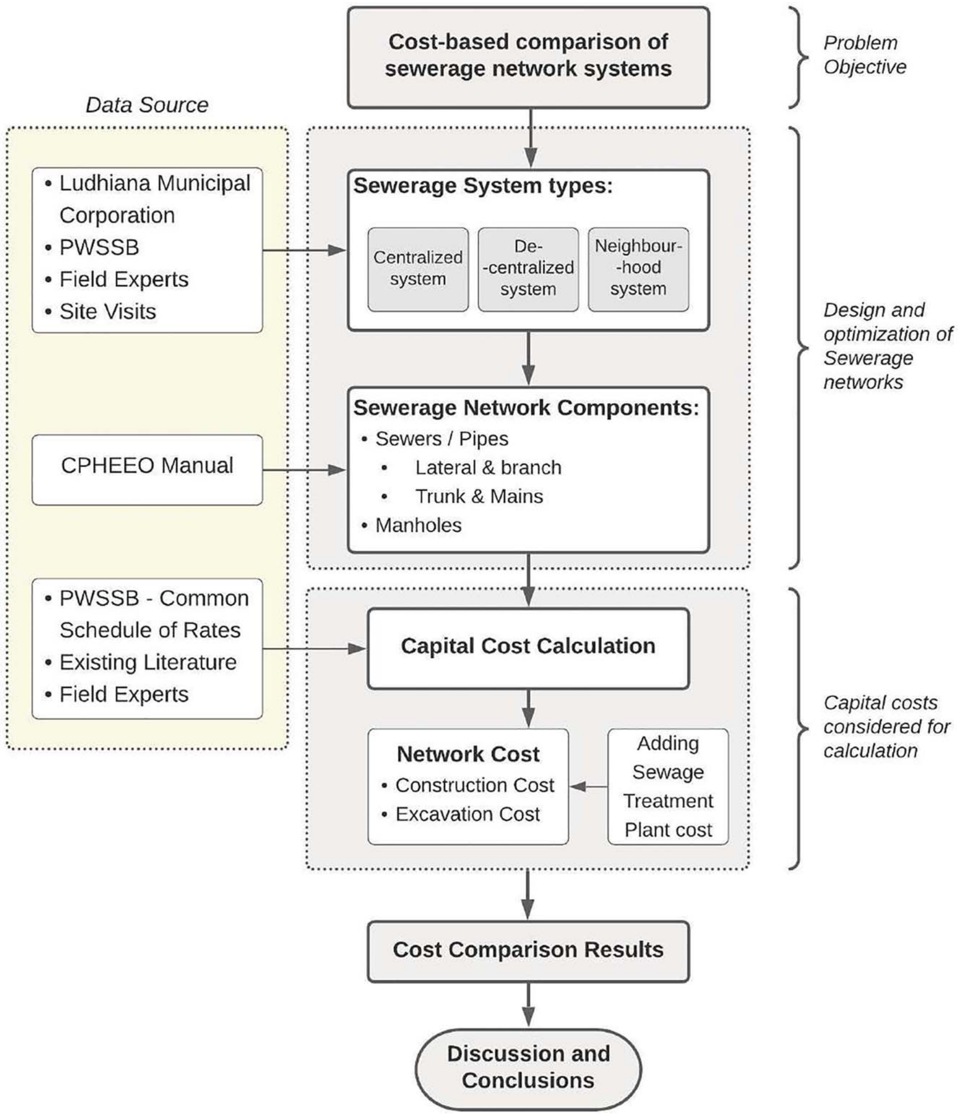

Fig. 1. Methodology flowchart for the cost comparison of sewerage network systems.

Scenarios

The sewerage systems were selected at three scales: the centralized and decentralized, and neighborhood levels, as shown in Fig. 3. Both the systems were located in the existing Balloke sewerage zone of the city, served by the Balloke STP. The centralized system covered the largest area and was connected to the remotely located Balloke treatment unit in the city's outskirts. For comparative purposes in this study, the decentralized system was selected within the area demarcated for the centralized area and was 1/7.5th of the centralized system's area. Similarly, the neighborhood network was considered within the decentralized area and was 1/12th of the decentralized system's area.

Three scenarios as outlined in Table 2 were finalized as per the types and scales of sewerage systems to be compared. The first two scenarios involved designing the trunk and main sewer network for centralized and decentralized systems, respectively, along with their treatment units. The network design was limited to the trunk and main sewer lines only for centralized and decentralized systems considering the large area and manual design constraints.

A third scenario called the neighborhood case was considered in this study to calculate the branch/lateral network costs for the centralized and decentralized systems. The branch/lateral network was designed, and costs were computed in a small area and then extrapolated for the larger centralized and decentralized areas to obtain the total network costs.

Centralized System

The Balloke sewerage zone was considered for selecting the centralized area in the city, which is spread over 55% of the city's total area (88 km^2). Because this is a considerably large area for redesigning the sewer network system, a smaller part of this area was defined by identifying physical boundaries within this sewerage zone and was isolated for carrying out the study. The selected zone for the centralized network system, as shown in Fig. 4, covered an area of 4.7 km^2. Considering a standard population density of 15,000 people per km^2, the population for this area was estimated to be around 413,240. The water supply for this area was estimated as 220 liters per capita per day (LPCD), which is the average water supply rate for Ludhiana city (PUDA 2011). According to this, the total water supply demand for the area's residing population was calculated to be around 90.9 million liters day (MLD). The CPHEEO (2013) manual suggests that wastewater generation be taken as 80% of the water supply. Therefore, the total wastewater generation for the selected area was estimated to

J. Urban Plann. Dev., 2023, 149(3): 05023016

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

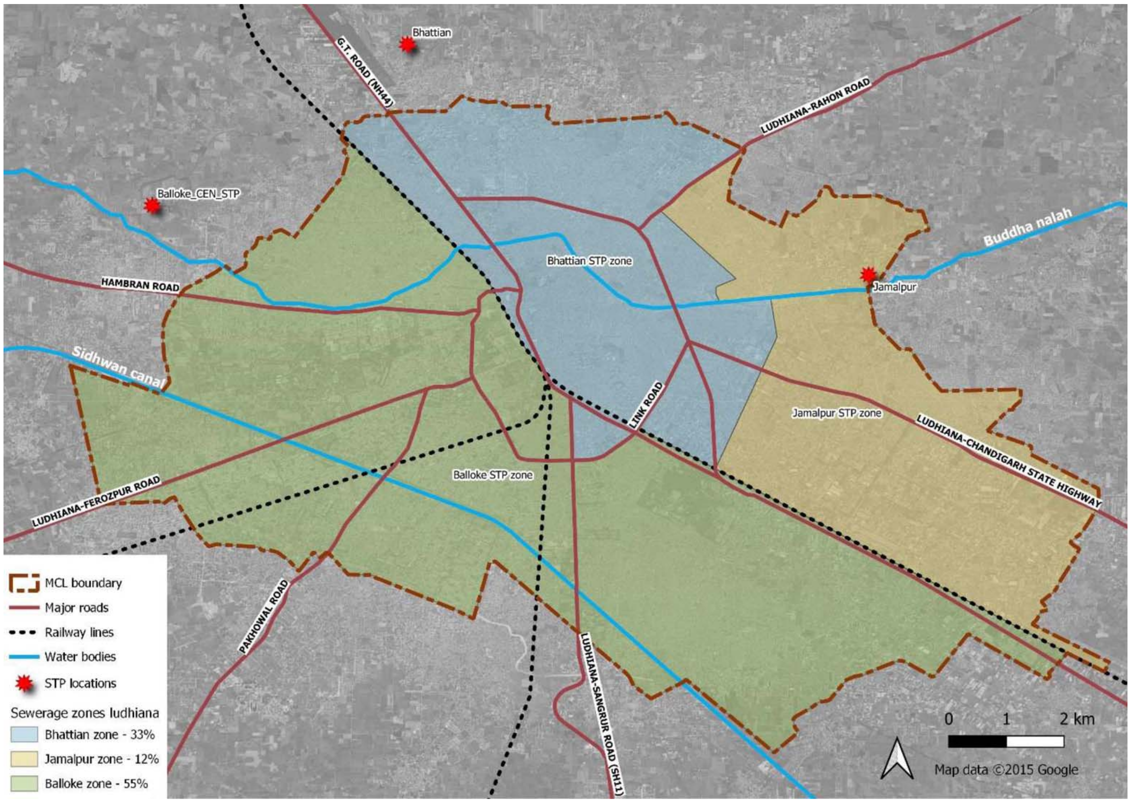

Fig. 2. Sewerage zones of Ludhiana. (Map data © 2015 Google.)

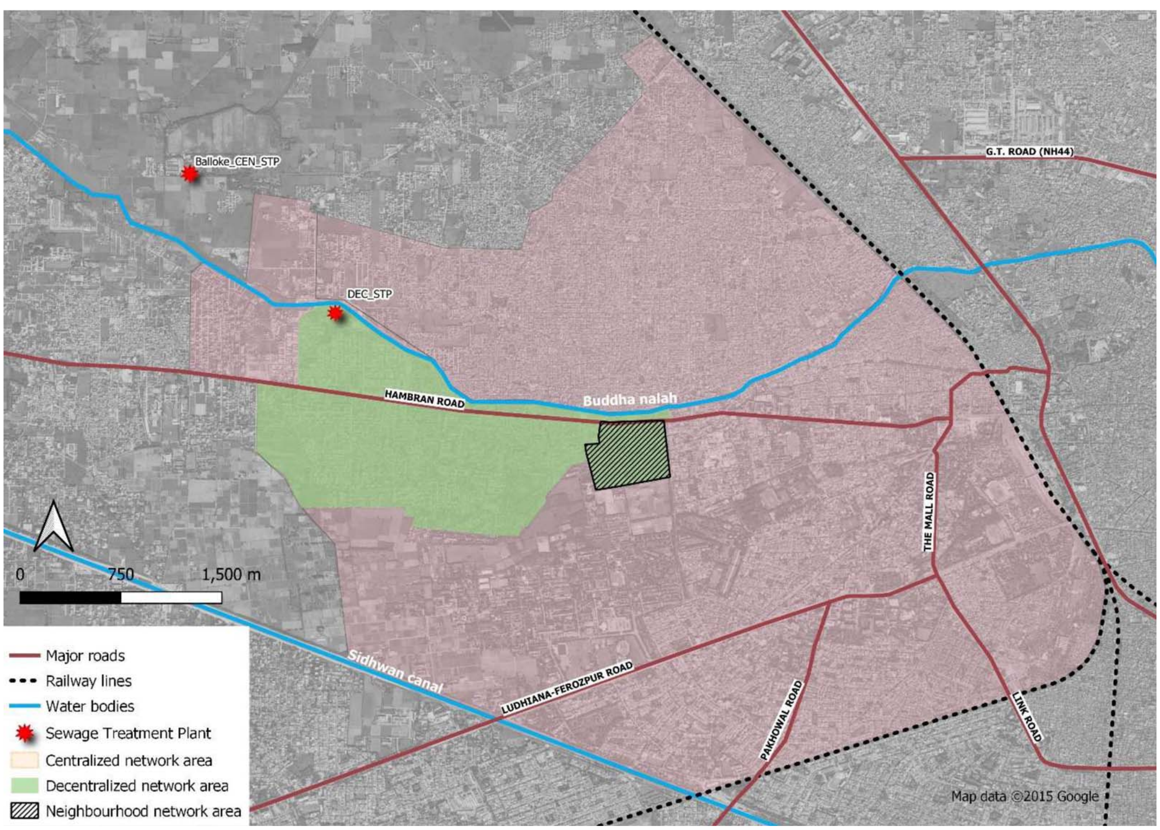

Fig. 3. Selected scenarios with their treatment plant locations. (Map data © 2015 Google.)

Table 2. Specifications of the selected three scenarios

Sr. no.	Network type	Area (in ha)	Population (pop. density 150 people/ha)	Water supply (in MLD, considering 220 LPCD)	Wastewater generation (in MLD)
1	Centralized	2,754.9	413,000	90.8	72.7
2	Decentralized	363.77	54,566	12	9.6
3	Neighborhood	30.3	4,548	10	0.8

be 72.7 MLD. So, the treatment plant for this area shall have the capacity to treat 72.7 MLD of wastewater. The topography for this area is primarily flat with a gentle slope in the northwest direction (refer to Fig. S1 in SI). The ground elevation levels range from 248 to 236 m, which were adopted from the DEM data provided by USGS Earth explorer (USGS 2020). The existing topographical situation in this area indicates that the existing location of the Balloke STP is suitable for the treatment plant. Hence, the existing location of STP was retained.

Decentralized System

The zone for the decentralized system, as shown in Fig. 5, was selected considering the location of the prominent Haibowal dairy complex in the city. This zone falls in administrative ward numbers 55 and 28 of the city. The topography for this area is mostly flat, with a gentle slope toward the northwest direction (refer to Fig. S2 in SI). The ground elevation levels range from 244 to 233 m, as adopted from the digital elevation model (DEM) data provided by USGS (2020). Analyzing the existing topography of the study area suggests that the Haibowal Dairy Complex area, which is situated toward the northwest lower part of this area, is a potential location for the treatment plant. The availability of vacant land in the dairy complex further supports this choice of location.

Neighborhood System

A neighborhood-level network was designed to calculate the cost of lateral and branch sewer pipes for the centralized and decentralized networks. This was done by identifying a small area, and its network was designed as an extended connection to the existing trunk and main sewer network of the decentralized network. The designed neighborhood network has since been used for calculating the cost of the lateral and branch sewers.

As the name suggests, this area is considered at a neighborhood level consisting of planned colonies. The selected area was located within the decentralized area boundary. The neighborhood network covers an area of approximately 0.3 km^2, which is 1/12th of the decentralized area and 1/100th of the centralized area. The limits of the neighborhood network were defined by the surrounding

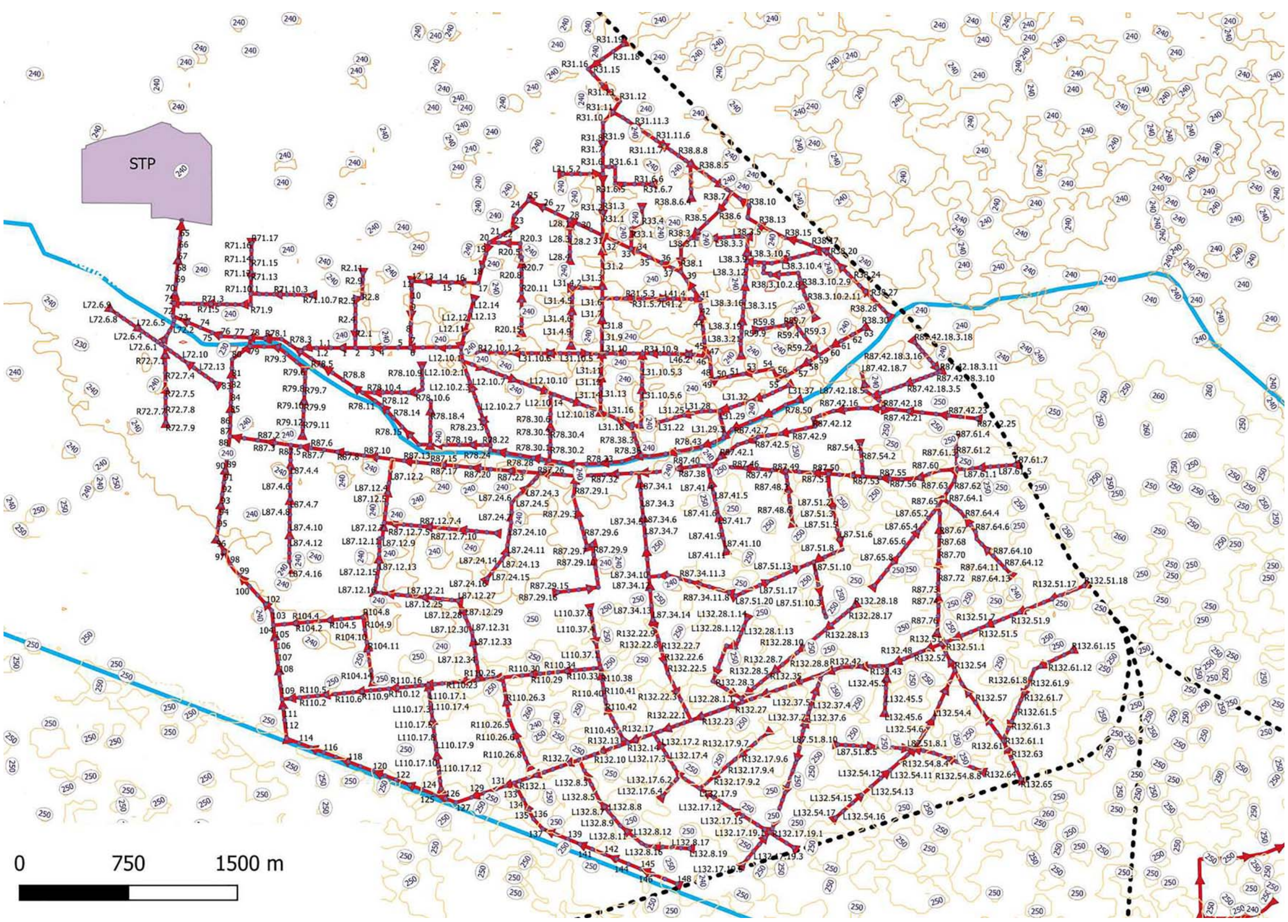

Fig. 4. Layout of a designed centralized sewerage network.

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

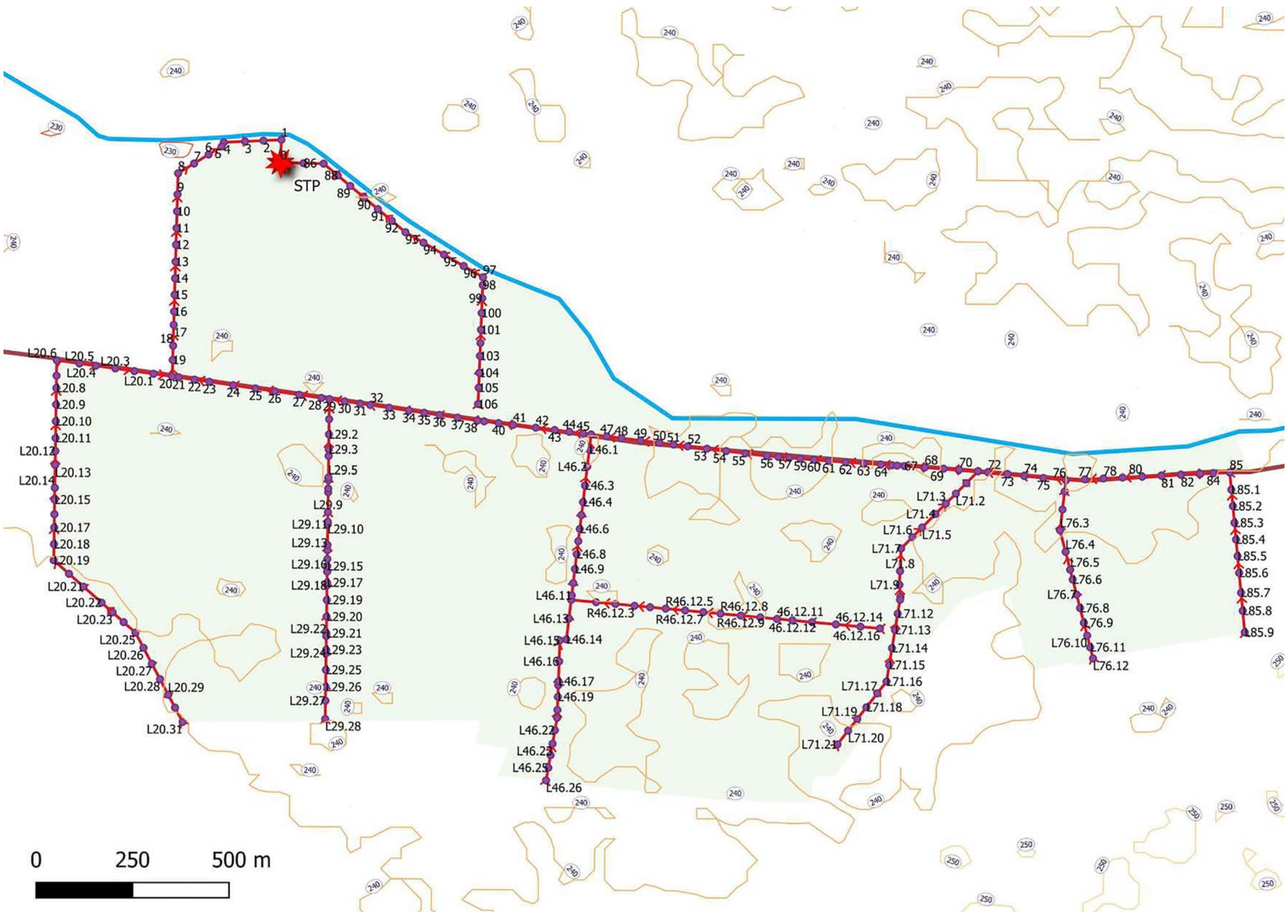

Fig. 5. Layout of a designed decentralized sewerage network.

secondary and tertiary roads. Because this is a small area, the topography is mostly flat with a very gentle slope in the northwest direction (Fig. S3).

The complete network was designed considering that it has to join one of the main sewer lines of the decentralized and centralized networks. The network comprises only the lateral and branch links laid out along the tertiary roads of the selected zone. Only the sewer links between manhole numbers 0–11 have been considered for preparing the layout to join it with the main link (Fig. 6). However, the main sewer costs have not been counted for the network specifications and cost calculations to avoid double-counting when extrapolated for a larger area.

Design and Estimation

The sewer network was designed considering the existing contextual characteristics such as topography, population density, etc., along with sewer specifications such as size, type, material, and so on. Once the sewer network layout was finalized, the network optimization was performed considering the standard specifications for various parameters such as peak flows, sewer diameters, sewer slope, velocity, excavation depth, etc., using the guidelines provided by the CPHEEO (2013) to design and construct sewers. The network layout was finalized in QGIS, which is an open-source software, while the calculations for the sewer network design were performed in Microsoft Excel. The basic information, such as the city's population, rainfall, and STP capacities, was sourced from readily available government reports such as the Census of India, Ludhiana master plan report, and so on. The water consumption and wastewater generation quantities were calculated using the standard guidelines provided in the CPHEEO manual. All the factors considered for the design process specific to each of the scenarios are mentioned in Table 3. Also, the total sewer length and the number of manholes in the three scenarios are provided in the same table.

Cost Analysis

The economic evaluation of the selected sewerage network systems was limited to capital cost calculation. The data for capital cost calculation were sourced from the Common Schedule of Rates provided by the Punjab Water Supply and Sewerage Board (PWSSB 2014). The total cost included construction and excavation costs for the sewer pipes and manholes. The cost extrapolation was performed to bring all the costs to a uniform scale for easier and meaningful comparison using the following steps:

- The cost of the neighborhood network was extrapolated for both decentralized and centralized scales separately to compute the cost share of lateral and branch networks in these systems, which had not been included otherwise.
- The cost of the decentralized network was extrapolated for the centralized scale using the area as an extrapolation factor.
- The cost of the treatment unit was added to the network cost calculations for computing the capital cost of the total system. The treatment costs for both systems were considered in terms of INR per MLD of the wastewater discharge under the condition of achieving the full scale of economy, which were sourced from the literature and field experts (Singh and Gupta 2018;

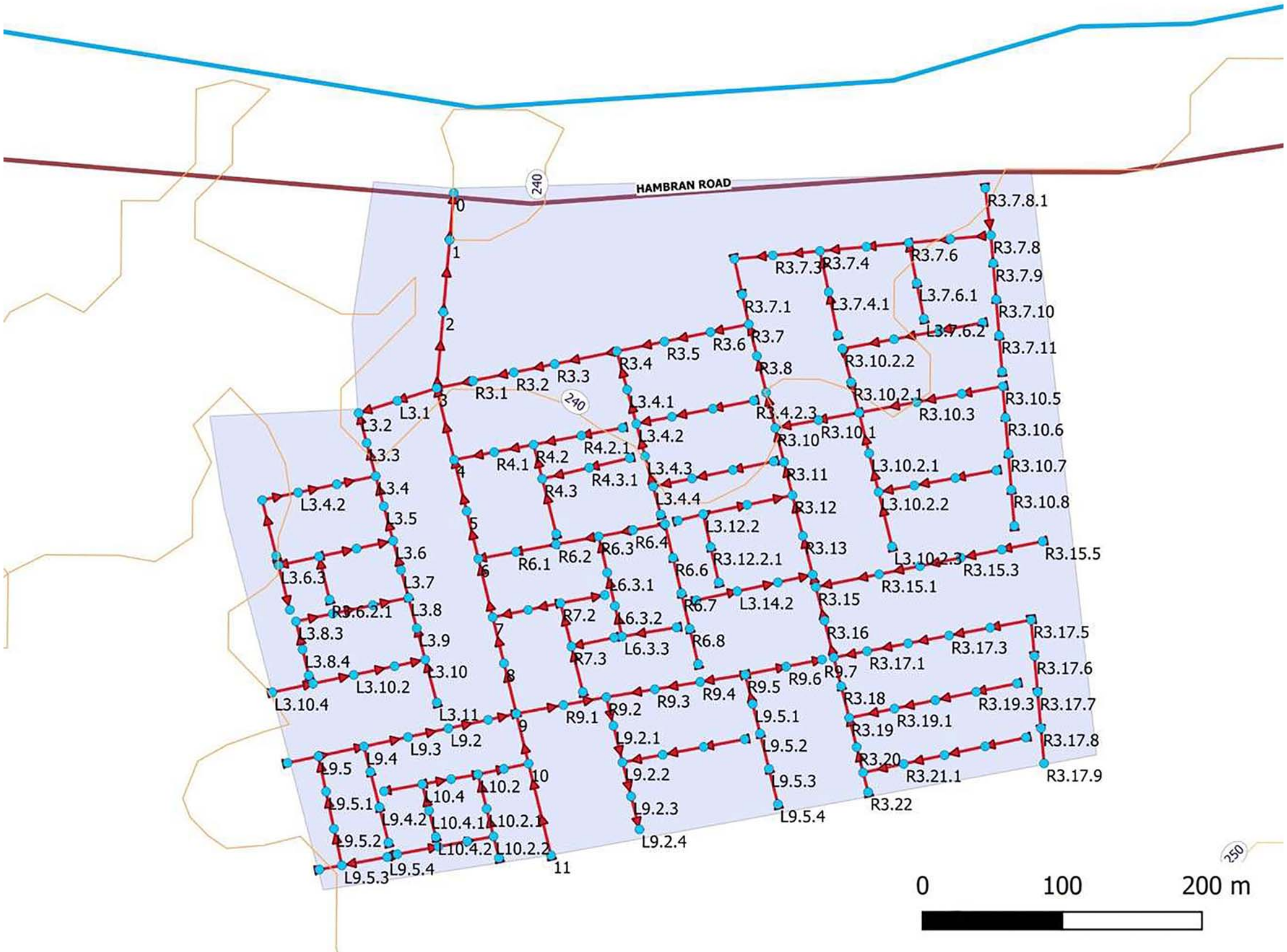

Fig. 6. Neighborhood Case I sewerage network layout.

Singh et al. 2016). The capital cost of the STP for the centralized area was estimated as 6 million INR per MLD, whereas the capital cost of the STP for the decentralized area was estimated as 8 million INR per MLD. The higher cost reflects the reduced scale of the economy for capital costs in decentralized systems.

Results and Discussion

The cost comparison results of the three systems have been described in this section along with a discussion on the additional benefits offered by the decentralized systems. Further, a planning model for the holistic implementation of the three systems in an urban area has also been presented. Lastly, the limitations of the present work along with the scope of future works have been discussed.

Economic Comparison

The total capital costs of centralized and decentralized networks, which include costs related to sewer pipes, excavation, laying of pipes, manholes, and STP, are given in Table 4. The economic comparison shows that the centralized and decentralized collection systems have almost similar equivalent capital expenditures for Ludhiana. The cost trends were also compared for different cost components, i.e., sewer pipe costs versus excavation costs and total sewer pipe costs versus total manholes costs for both centralized and decentralized systems, which did not show any significant cost differences either (as shown in Fig. 7). Interestingly, this analysis shows that the sewer cost is 1.7 times higher than the excavation cost and about 2.6 times the manholes costs, respectively. This signifies the importance of reconsidering the network length while planning sewerage infrastructure. The network costs for both

Table 3. Factors considered for sewer network design in three scenarios

Sr. no.	Factors	Centralized	Decentralized	Neighborhood
1	Population density	150 people/ha	150 people/ha	150 people/ha
2	Infiltration rate	5,000 L/ha/day	5,000 L/ha/day	5,000 L/ha/day
3	Peak factor	2	2.25	3
4	Minimum sewer diameter	160 mm	160 mm	160 mm
5	Minimum velocity	0.57–0.6 m/s	0.57–0.6 m/s	0.3 m/s
6	Minimum depth	1.15 m	1.15 m	0.9 m
7	Sewer length	85,130.23 m	11,009.04 m	5,733.10 m
8	Number of manholes	1,289	250	201

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Table 4. Total costs of the sewerage systems

Type of sewerage system	Total sewerage network cost (in million INR)	STP cost (in millions)				Total system cost (in million INR)
		Capacity (MLD)	Number of STPs required for covering the entire area	Cost (millions per MLD)	Total STP cost (in million INR)	
Centralized	1,286.45	72.7	1	6	436.2	1,722.65
Decentralized	1,274.43	9.6	7.57	8	581.6	1,856.03

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

centralized and decentralized networks are calculated as INR 0.467 million/ha. The results will be similar for other cities with a flat topography; however, these results might vary in case of different topographies.

Several studies have compared the costs of centralized and decentralized networks. Few studies have suggested that decentralized systems are more cost-efficient for sparsely populated areas, while conventional (centralized) systems might be less capital-intensive for densely populated and well-developed areas (Bakir 2001). However, results from the current study on Ludhiana present a different outcome where the capital costs for both systems are comparable for a population density of 150 people/ha in a well-developed urban area. This result signifies the critical role of O&M costs of treatment systems while planning the sewerage infrastructure of a given city. In developing countries such as India, capital costs are usually sourced through national schemes or funding by international organizations. In this scenario, the consideration of O&M costs in decision-making gains prominence. This aspect is also highlighted by Kalbar (2021a), wherein the role of O&M costs is shown to be dominant in the life cycle costing of wastewater treatment.

Mara (2012) has reported that the conventional underground drainage systems become economical beyond 150 people/ha. The difference in results can be attributed to parameters such as topographical variations, population density, urban form, and land use. For example, Ho and Anda (2006) have highlighted the possibilities of diseconomy of scale in the case of centralized systems if sewage has to be pumped through long distances or there is an excessive inlet of stormwater or wastewater into the sewerage system. Hence, the inclusion of pumping stations and their associated costs might reflect different results from those observed in this study, which considers an ideal gravity-flow scenario. This suggests that considering the study area's topography while planning the sewer network to utilizing gravity to the maximum possible extent, can create an energy-efficient infrastructure.

Other studies on similar topics have suggested that the initial capital investments for the collection system of centralized systems are higher than that of decentralized systems (Libralato et al. 2012; Roux et al. 2011). Studies have reported that decentralized sewer capital costs are lower than that of centralized systems by 40%–50% (Maurer et al. 2005; Jung et al. 2018). A study conducted by Jung et al. (2018) in Alibaug draws a cost comparison between centralized wastewater management systems and cluster-type decentralized wastewater management systems showing a difference of 40%–45% in the cost of decentralized systems as compared with that of centralized systems. The observations from the aforementioned studies contradict the results from our study, which do not show significant differences in the costs of the three systems. This variation can be explained by the fact that the cost of sewerage systems varies significantly with contextual characteristics such as land topography, population density, wastewater loads, and so on.

Further, in the present work, the cost of sewer pipes is found to have a higher impact on the total sewer cost than its excavation cost. A comparison between the total sewer cost and the total manhole cost shows that the sewer cost has a higher impact on the overall network cost. It can therefore be inferred that optimizing the

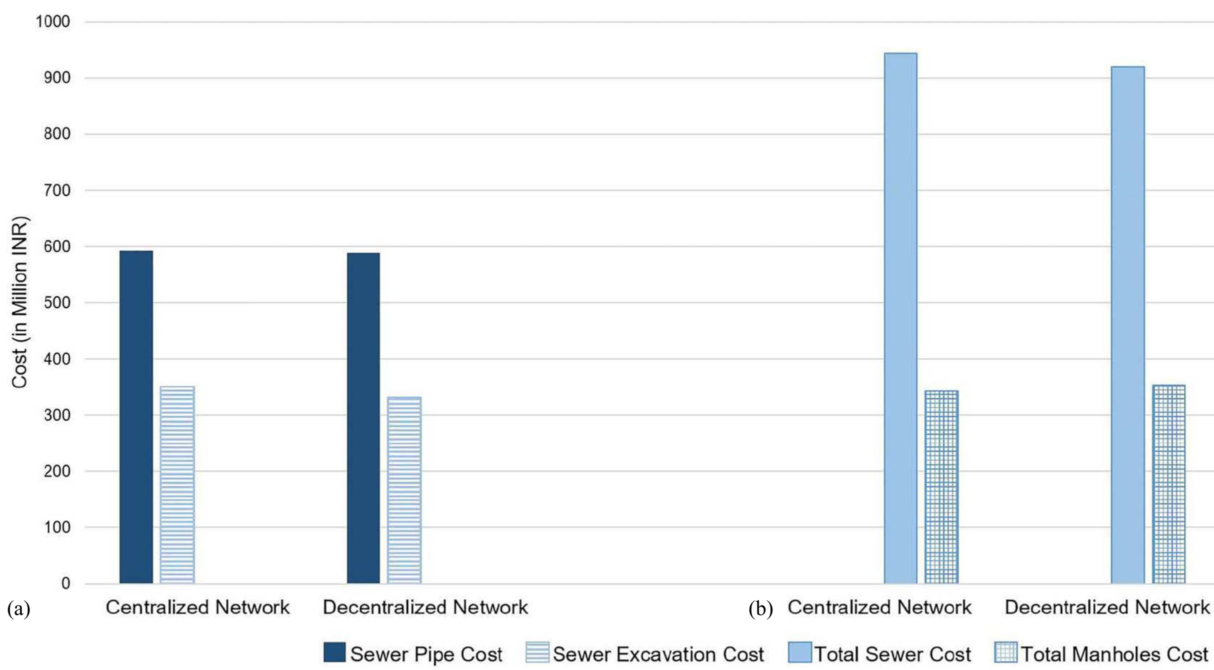

Fig. 7. Cost comparison chart for (a) sewer pipe cost versus sewer excavation cost; and (b) total sewer cost versus total manholes cost.

sewer pipe cost according to various parameters such as the material selection, sizes, depths, and design life span might help considerably reduce the overall collection system costs. The study by Eggimann et al. (2015) models the optimal degree of centralization for sewerage systems but does not include manholes in the sewer design and cost computation. Our study shows that manholes are an integral component of the sewerage network system, which holds a considerable share in the total cost of the network system and should also be accounted for in economic assessments. The depth of sewers increases with increased network length in a centralized system, more often in flat terrains. In such situations, the construction of manholes at higher depths is required, which implies higher costs. However, decentralized systems require a shorter sewer network that is laid at relatively shallow depths, thereby reducing the cost component of manholes.

Other Benefits of Decentralized Systems

The capital cost of decentralized systems was nearly similar when compared with the centralized system costs in this study. However, decentralized systems offer additional benefits that cannot be readily measured. Firstly, they provide water recycling and reuse opportunities for various urban uses such as landscaping and agriculture, nonpotable domestic and industrial uses, and replenishing surface water, thereby reducing the load on water supply infrastructure and also promoting a circular economy (Arceivala and Asolekar 2008; Ho and Anda 2006; Kakwani and Kalbar 2020). Secondly, the effort for planning, designing, and implementing decentralized systems is lower than that for conventional centralized systems. Decentralized systems allow for phased investments, thus reducing the investment loads of the municipal authorities (Jung et al. 2018). This can also cater to uncertain and dynamic factors such as population growth and changing land-use patterns. Thirdly, the environmental benefits of these systems outweigh their costs, as they have a higher potential for achieving environmental sustainability (Liang and Dijk 2008; Ho and Anda 2006), which can help urban local bodies attain sustainable development goals. Further, natural treatment systems such as constructed wetlands having enormous economic and environmental benefits can be conveniently implemented in a decentralized manner. Centralized systems, however, adopt the conventional mechanized treatment systems that pose operational problems in the long run. Considering the technoeconomic and environmental sustainability, Kalbar (2021b) has identified the approach of hybrid wastewater treatment systems (defined as the strategic integration of mechanized and nonmechanized/natural treatment systems) as a better alternative in land-constrained areas than mechanized or natural systems implemented in isolation. Fourthly, a decentralized system can offer higher energy efficiency than centralized systems because they do not require the installation of pumping stations used to prevent deep excavations in the case of centralized systems.

Additionally, greater system resilience and adaptability are offered by decentralized systems, such as lower vulnerability, reduced failure risks, higher recovery amidst power cuts and improper maintenance, because the risk is distributed across multiple smaller systems (Bernal and Restrepo 2012; Dahlgren et al. 2013; Jung et al. 2018; Leigh and Lee 2019). Also, decentralized systems are capable of responding to the changing goals of wastewater treatment, making them more flexible than centralized systems (Spiller et al. 2015). Lastly, decentralized systems can ensure maximum economic benefits and a larger market for recycled water use if they are optimized in terms of the degree or scale of decentralization.

Learnings for Other Cities in India

The present study suggests that both centralized and decentralized systems have certain advantages and disadvantages from different aspects. A holistic approach can be adopted to obtain maximum benefits from these systems and provide an optimized solution for infrastructural planning in urban areas. Planning guidelines can be framed according to the compatibility of each system. A basic model proposed in Fig. 8 presents the idea of implementing different systems in combination depending on the local urban characteristics.

Most cities, especially in India, grow outward from a dense core area. Population density is found to be lower in the outer areas surrounding the central core of the city (Mookherjee 2004; Mondal and Banerjee 2021). A study by Kotharkar and Bahadure (2020) examined the changes in the spatial distribution of built-up areas and population densities in the core urban zone, intermediate zone, and peripheral zone of eight selected Indian million-plus cities. They reported that the population densities decrease from the urban core to the peripheral parts of the cities and vary in the range of 150–400 person per hectare (pph) for the urban core, 60–200 pph for the intermediate zone, and 10–60 pph for the peripheral zone for the selected eight cities as per the population data for 2010. Considering this growth pattern, the cities can be divided into three zones—a highly developed dense urban core area (Zone 1), surrounded by a lesser densely populated immediate extension of the core area (Zone 2), and finally, a peripheral area that is sparsely populated and of low density (Zone 3). Sewerage systems can be provided considering the varying densities in the urban areas such that:

- The core areas of the city that are generally highly developed and densely populated can be covered with a gravity-flow underground network connected to a wastewater treatment unit.
- The extension area surrounding the dense core areas in a town is generally found to be undergoing development but has less dense population than the city cores. So, these areas can be provided with a system of individual septic tanks connected to a network of open drains. When these areas undergo complete development in the future, they can be connected to the underground network existing in the core areas or provided with separate treatment systems.

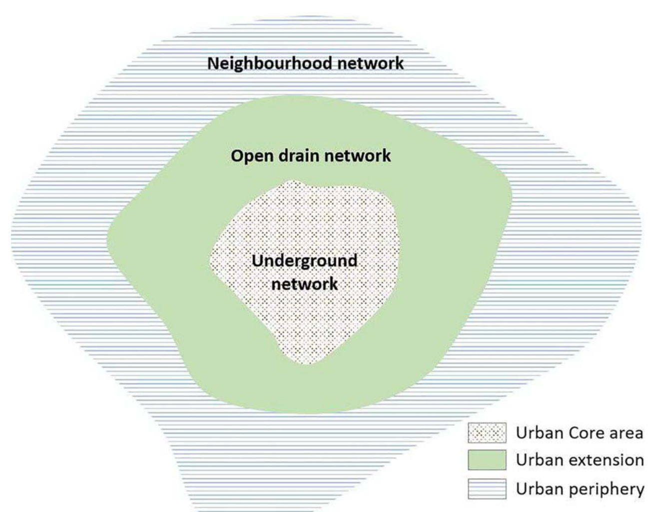

Fig. 8. Provision of sewerage systems as per population densities in an urban area. Zone 1: dense urban core, Zone 2: urban extension (medium density), and Zone 3: urban periphery (low density).

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.

- The peripheral areas are located in the outermost fringes of the city and are generally underdeveloped and sparsely populated. A community-based development pattern is observed in these areas, which is suitable for the provision of a neighborhood or a community-level sewerage system. These systems can offer the benefits of water reuse at the community level, making the recycled water supply infrastructure economically viable in the newer and developing city areas.

Limitations and Future Work

The current study is limited to an economic assessment of selected sewerage systems. Under the economic aspect, only capital costs were considered for the cost comparison of sewerage network systems. A more in-depth study can be performed as part of the future scope by replicating similar studies in other cases with different contexts such as varying population density, different topographic conditions, and urban form, which will significantly contribute to this research area. Optimizing the degree of decentralization is another novel concept that can be explored as a part of future research work. This study has not considered the environmental, social, and governance aspects, which are becoming essential to assess sewerage systems based on a holistic perspective.

The authorities framed the current guidelines on sewerage network design with a focus on the application of only centralized systems, which should also be extended to decentralized systems for better choices. The optimum scale of decentralization is an important area that needs further exploration for deriving the best decision outputs for various contexts, because the economic impacts of these sewerage systems vary contextually.

Conclusions

Cities are witnessing growing challenges related to freshwater scarcity, wastewater recycling, meeting sustainable development goals, and emerging challenges due to climate extremes. These demand sustainable and resilient infrastructure, which can be achieved using decentralized infrastructure planning because it offers multiple environmental, economic, and social benefits. This study has assessed capital costs for centralized and decentralized systems based on a detailed sewer design in a real-life case study from India. The results have shown that the costs of both sewerage network systems (at different scales) are almost the same for the chosen case, with a population density of 150 people/ha and a gently sloping topography. As the capital costs for the systems were comparable, the focus of decision-making should be on the O&M costs, and further research should explore the life cycle costs of the sewerage infrastructure. Also, awareness generation regarding the other nontangible environmental and social benefits of decentralized systems should be carried out among urban local bodies. For example, a decentralized infrastructure is more resilient and can cope with climate extremes more effectively than centralized systems. Policy guidelines encouraging the adoption of decentralized systems in various settings of urban, periurban, and rural areas should be framed. Further, the analysis should be extended from a gently sloping topography to hilly and undulating terrains and for varying population densities to understand the role of urban settlement characteristics in the liquid waste management of a city.

The comparison of centralized and decentralized systems shows that both systems have advantages and disadvantages. Hence, the scale of decentralization will play a key role in realizing the benefits of both systems. The present work represents only two extremes of centralized and decentralized systems; however, the methodology should be extended to quantify an optimal scale of decentralized systems based on a multiple parameter-based sewer design. At the same time, it should be realized that a one-size-fits-all approach is not applicable to urban water infrastructure; hence, case-specific decisions should be taken based on an in-depth understanding of the local context. The urban local bodies need to understand the significance of scale in implementing sewerage infrastructure and should analyze the local geographic and economic dimensions before planning sewerage infrastructure. Such a holistic planning and design approach will help achieve sustainable liquid waste management.

Data Availability Statement

Some or all data, models, or codes used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgments section.

Acknowledgments

The authors thank the Ludhiana Municipal Corporation for providing data, maps, and documents related to the existing sewer network. The authors received partial funding for this work from the Department of Science and Technology, Government of India, through the project "Fast Forward to SDG6: Acceptable and Affordable Water in Secondary Indian Cities (4WARD)" Project Number DST/TM/EWO/WTI/2K19/UWS-03(C4). The authors also thank the editor and the two anonymous reviewers whose comments have substantially helped improve the quality of the manuscript.

Supplemental Materials

Table S1 and Figs. S1–S3 are available online in the ASCE Library (www.ascelibrary.org).

References

Arceivala, S. J., and S. R. Asolekar. 2008. *Wastewater treatment for pollution control and reuse*. 3rd ed. New York: Tata McGraw-Hill.

Bakir, H. A. 2001. "Sustainable wastewater management for small communities in the Middle East and North Africa." *J. Environ. Manage.* 61 (4): 319–328. https://doi.org/10.1006/jema.2000.0414.

Barron, N. J., et al. 2017. "Towards water sensitive cities in Asia: An interdisciplinary journey." *Water Sci. Technol.* 76 (5): 1150–1157. https://doi.org/10.2166/wst.2017.287.

Bernal, D. P., and I. Restrepo. 2012. "Key issues for decentralization in municipal wastewater treatment." In *Proc., 12th edition of the World Wide Workshop for Young Environmental Scientists—Urban Waters: Resource or Risks?* Lyon, France: HAL.

Burian, S. J., S. J. Nix, R. E. Pitt, and S. R. Durrans. 2000. "Urban wastewater management in the United States: Past, present, and future." *J. Urban Technol.* 7 (3): 33–62. https://doi.org/10.1080/713684134.

CDP (City Development Plan). 2007. *Ludhiana City Development Plan: Vision 2021*. Jawaharlal Nehru National Urban Renewal Mission (JNNURM).

CPCB (Central Pollution Control Board). 2021. "National inventory of sewage treatment plants." Accessed September 21, 2020. https://cpcb.nic.in/openpdffile.php?id=UmVwb3J0RmlsZXMvMTIyOF8xNjE1MTk2MzIyX21lZGlhcGhvdG85NTY0LnBkZg==.

CPHEEO (Central Public Health and Environmental Engineering Organization). 2013. "Manual on sewerage and sewage treatment."

Accessed September 21, 2020. http://www.indiaenvironmentportal.org.in/files/file/Manual on sewerage and sewage treatment.pdf.

Dahlgren, E., C. Göçmen, K. Lackner, and G. V. Ryzin. 2013. "Small modular infrastructure." *Eng. Econ.* 58 (4): 231–264. https://doi.org/10.1080/0013791X.2013.825038.

Eggimann, S., B. Truffer, and M. Maurer. 2015. "To connect or not to connect? Modelling the optimal degree of centralisation for wastewater infrastructures." *Water Res.* 84: 218–231. https://doi.org/10.1016/j.watres.2015.07.004.

Hellström, D., U. Jeppsson, and E. Kärrman. 2000. "A framework for systems analysis of sustainable urban water management." *Environ. Impact Assess. Rev.* 20 (3): 311–321. https://doi.org/10.1016/S0195-9255(00)00043-3.

Ho, G., and M. Anda. 2006. "Centralised versus decentralised wastewater systems in an urban context: The sustainability dimension." In *Proc., 2nd IWA Leading-Edge Conf. on Sustainability*, 80–89. London, UK: IWA Publishing.

Hophmayer-Tokich, S. 2006. "Wastewater management strategy: Centralized versus decentralized technologies for small communities." *CSTM-Reeks* 271 (271): 27.

Jung, Y. T., N. C. Narayanan, and Y. L. Cheng. 2018. "Cost comparison of centralized and decentralized wastewater management systems using optimization model." *J. Environ. Manage.* 213: 90–97. https://doi.org/10.1016/j.jenvman.2018.01.081.

Kakwani, N. S., and P. P. Kalbar. 2020. "Review of circular economy in urban water sector: Challenges and opportunities in India." *J. Environ. Manage.* 271: 111010. https://doi.org/10.1016/j.jenvman.2020.111010.

Kalbar, P. P. 2021a. "Need for adopting hybrid treatment systems to reduce O&M costs of sewage treatment and recycling in India." *J. Indian Water Works Assoc.* LIII (4): 247–252.

Kalbar, P. P. 2021b. "Hybrid treatment systems: A paradigm shift to achieve sustainable wastewater treatment and recycling in India." *Clean Technol. Environ. Policy* 23 (4): 1365–1373. https://doi.org/10.1007/s10098-021-02034-x.

Kamal, A. S. M., K. Goyer, T. Koottatep, and A. T. M. N. Amin. 2008. "Domestic wastewater management in South and Southeast Asia: The potential benefits of a decentralised approach." *Urban Water J.* 5 (4): 345–354. https://doi.org/10.1080/15730620802030056.

Kotharkar, R., and P. Bahadure. 2020. "Achieving compact city form through density distribution: Case of Indian cities." *J. Urban Plann. Dev.* 146 (1): 04019022. https://doi.org/10.1061/(asce)up.1943-5444.0000529.

Leigh, N. G., and H. Lee. 2019. "Sustainable and resilient urban water systems: The role of decentralization and planning." *Sustainability (Switzerland)* 11 (3): 918. https://doi.org/10.3390/su11030918.

Liang, X., and M. P. V. Dijk. 2008. "Economic and financial analysis of decentralized water recycling systems in Beijing." In *Proc., 3rd SWITHC Scientific Meeting*. Belo Horizonte, Brazil: SWITCH Scientific.

Libralato, G., A. V. Ghirardini, and F. Avezzù. 2012. "To centralise or to decentralise: An overview of the most recent trends in wastewater treatment management." *J. Environ. Manage.* 94 (1): 61–68. https://doi.org/10.1016/j.jenvman.2011.07.010.

Luby, S. P., J. Davis, R. R. Brown, S. M. Gorelick, and T. H. F. Wong. 2020. "Broad approaches to cholera control in Asia: Water, sanitation and handwashing." *Vaccine* 38: A110–A117. https://doi.org/10.1016/j.vaccine.2019.07.084.

Mara, D. 2012. "Sanitation: What's the real problem?" *IDS Bull.* 43 (2): 86–92. https://doi.org/10.1111/j.1759-5436.2012.00311.x.

Massoud, M. A., A. Tarhini, and J. A. Nasr. 2009. "Decentralized approaches to wastewater treatment and management: Applicability in developing countries." *J. Environ. Manage.* 90 (1): 652–659. https://doi.org/10.1016/j.jenvman.2008.07.001.

Maurer, M., O. Rothenberger, and T. A. Larsen. 2005. "Decentralised wastewater treatment technologies from a national perspective: At what cost are they competitive?" *Water Sci. Technol. Water Supply* 5 (6): 145–154. https://doi.org/10.2166/ws.2005.0059.

Mondal, D., and A. Banerjee. 2021. "Exploring peri-urban dynamism in India: Evidence from Kolkata Metropolis." *J. Urban Manage.* 10 (4): 382–392. https://doi.org/10.1016/j.jum.2021.06.004.

Mookherjee, D. 2004. "Cities in transition: Monitoring growth trends in Delhi urban agglomeration 1991–2001." *Dela* 21: 195–203. https://doi.org/10.4312/dela.21.195-203.

Nanninga, T. A., I. Bisschops, E. López, J. L. M. Ruiz, D. Murillo, L. Essl, and M. Starkl. 2012. "Discussion on sustainable water technologies for peri-urban areas of Mexico city: Balancing urbanization and environmental conservation." *Water (Switzerland)* 4 (3): 739–758. https://doi.org/10.3390/w4030739.

Nawrot, T., R. Matz, R. Błazejewski, and M. Spychala. 2018. "A case study of a small diameter gravity sewerage system in Zolkiewka Commune, Poland." *Water (Switzerland)* 10 (10): 1358. https://doi.org/10.3390/w10101358.

PUDA (Punjab Urban Development Authority). 2011. "Master plan report Ludhiana-2031." Accessed September 4, 2020. https://www.puda.gov.in/sites/default/files/Ldh_rpt_2011.pdf.

Putri, P. W. 2017. "A decentralised approach to wastewater management in the urbanising region: The case of Jakarta, Indonesia." *Urbanisation* 2 (2): 83–97. https://doi.org/10.1177/2455747117740439.

PWSSB (Punjab Water Supply and Sewerage Board). 2014. "Common schedule of rates."

Reymond, P., R. Chandragiri, and L. Ulrich. 2020. "Governance arrangements for the scaling up of small-scale wastewater treatment and reuse systems—Lessons from India." *Front. Environ. Sci.* 8 (June): 72. https://doi.org/10.3389/fenvs.2020.00072.

Roux, P., I. Mur, E. Risch, and C. Boutin. 2011. "Urban planning of sewer infrastructure: Impact of population density and land topography on environmental performances of wastewater treatment systems." In *Proc., Int. Conf. on Life Cycle Management*. Eindhoven, The Netherlands: Eindhoven University of Technology.

Singh, N. K., P. Banyal, and A. A. Kazmi. 2016. "Techno-economic assessment of full scale MBBRs treating municipal wastewater followed by different tertiary treatment strategies: A case study from India." *Nat. Environ. Pollut. Technol.* 15 (4): 1311–1316.

Singh, N. K., A. A. Kazmi, and M. Starkl. 2015. "A review on full-scale decentralized wastewater treatment systems: Techno-economical approach." *Water Sci. Technol.* 71 (4): 468–478. https://doi.org/10.2166/wst.2014.413.

Singh, S., and A. B. Gupta. 2018. "Life cycle cost assessment of different sewage treatment technologies—A case study." *J. Indian Water Works Assoc.* 1: 169–174.

Sitzenfrei, R., and W. Rauch. 2014. "Investigating transitions of centralized water infrastructure to decentralized solutions—An integrated approach." *Procedia Eng.* 70: 1549–1557. https://doi.org/10.1016/j.proeng.2014.02.171.

Spiller, M., J. H. G. Vreeburg, I. Leusbrock, and G. Zeeman. 2015. "Flexible design in water and wastewater engineering—Definitions, literature and decision guide." *J. Environ. Manage.* 149: 271–281. https://doi.org/10.1016/j.jenvman.2014.09.031.

UN (United Nations). 2020. "The sustainable development goals report 2020." Accessed October 1, 2020. https://www.pps.org/category/placemaking.

UN-DESA (United Nations Department of Economic and Social Affairs). 2018. "World urbanization prospects." Accessed October 1, 2020. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf.

UN-WATER. 2015. "Wastewater management a UN-water analytical brief." Accessed September 22, 2020. https://www.unwater.org/publications/wastewater-management-un-water-analytical-brief/.

USGS. 2020. "USGS earth explorer." Accessed September 5, 2020. https://earthexplorer.usgs.gov/.

Wang, S. 2014. "Values of decentralized systems that avoid investments in idle capacity within the wastewater sector: A theoretical justification." *J. Environ. Manage.* 136: 68–75. https://doi.org/10.1016/j.jenvman.2014.01.038.

Woods, G. J., D. Kang, D. R. Quintanar, E. F. Curley, S. E. Davis, K. E. Lansey, and R. G. Arnold. 2013. "Centralized versus decentralized wastewater reclamation in the Houghton Area of Tucson, Arizona." *J. Water Resour. Plann. Manage.* 139 (3): 313–324. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000249.

Downloaded from ascelibrary.org by "Indian Institute of Technology, Bombay" on 04/18/23. Copyright ASCE. For personal use only; all rights reserved.