Economic Assessment of Centralized and Decentralized Sewerage Network Systems – A Case Study of Ludhiana City

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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 city for conducting a detailed economic comparison based on the network's capital costs for both systems. The decentralized

33 systems have shown almost similar capital costs as the centralized system in this study. Hence

34 both systems can be adopted based on capital cost. However, the study showed that

35 decentralized systems offer more water recycling opportunities, making them preferable to

36 centralized systems. The study also emphasizes that the choice of sewerage systems should be

37 context-specific to fetch maximum economic and environmental benefits.

38 **Keywords**: Wastewater management; Sewerage system; Centralized network;
39 Decentralized network; Economic assessment

40 **INTRODUCTION**

41   As urbanization is taking place globally, it has been observed that 55% of the world's

42 total population lived in urban areas in 2018, and it is expected to reach 68% by 2050 (UN-

43 DESA 2018). Urbanization, along with other factors such as population growth,

44 industrialization, change in land-use patterns, and poor water management, impose pressure on

45 water resources. Around the globe, 40% of the population is already facing water scarcity, and

46 water stress, the ratio of freshwater withdrawn to available renewable freshwater resources, is

47 expected to worsen in the future. Central and southern Asia and Northern Africa fall under high

48 water stress zones with a stress level as high as 70% (UN 2020). Since water is a renewable

49 resource and an essential element for human survival on earth, it needs to be adequately

50 managed, indicating the need for efficient wastewater management. The sixth goal among the

51 17 sustainable development goals of the United Nations, to be achieved by 2030, is, "Ensure

52 availability and sustainable management of water and sanitation for all" (UN 2020). However,

53 in the current scenario, only 20% of the globally generated wastewater is being treated, while

54 the remaining 80% enters the untreated water bodies (UN-WATER 2015). The situation is no

55 different for India, where only 28% of the total wastewater generated in Indian cities is being

56 adequately treated (CPCB 2021). The rest is directly discharged into water bodies,

57 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 (ULBs) to maintain the sewerage systems, high resource inefficiency, remote locations of Sewage Treatment Plants (STPs), and high investment and Operation & Maintenance (O&M) costs (CPHEEO 2013). Decentralized sewerage systems treating the wastewater near to the point of generation, on the other side, are being recognized as a viable alternative to the conventional centralized systems in terms of environmental favourability and the potential for water reuse (Jung, Narayanan, and Cheng 2018; Libralato, Volpi Ghirardini, and Avezzù 2012). However, the economic viability of these systems needs to be assessed as the economic criteria mainly govern the choice of sewerage infrastructure.

Wastewater management includes the 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 the urban water and wastewater systems (Hellström, Jeppsson, and

83 Kärrman 2000). However, the cost of sewer systems, an essential component of cost analysis,

84 is often excluded during their economic evaluation. Roux et al. (2011) reported in their study

85 that the sewer network has a considerable contribution to the overall environmental footprint

86 of the sanitation system and also emphasized the need to assess the economic impact of sewer

87 networks. In a conventional sewerage system, the collection network carries a significant

88 economic burden with a high share, of about 80%, in the overall capital costs of the system

89 (Libralato et al., 2012; Arceivala and Asolekar, 2008). Nawrot et al. (2018) have indicated in

90 their study that there is an opportunity to optimize the cost of collection systems by adequate

91 selection and sizing of its inventory.

92   As the attention is being shifted towards the overall optimization of urban sewerage

93 systems, it necessitates finding costs for the collection systems at various scales of

94 centralization (or decentralization) for a better comparison.

95 **Need for comparative assessment of centralized and decentralized sewerage systems**

96   An Indian city is typically dependent either on on-site systems or are partially/fully

97 covered by the underground sewer network/ open-drain network for wastewater management.

98 It has been reported that in 2021, the total installed sewage treatment capacity of the Sewage

99 Treatment Plants (STP) in urban centers of India is just 44% of the total sewage generation

100 (CPCB 2021). Furthermore, only 64% of the installed sewage treatment capacities are utilized,

101 indicating the inadequacies in the sewage collection and sewage treatment facilities in Indian

102 cities. As urban development is proceeding at a fast pace, there is a need to serve these cities

103 with fully laid out sewerage systems to overcome the sanitation issues. However, achieving

104 100% sewerage systems is not practically feasible on the ground. In this background, adopting

105 decentralized systems along with a centralized sewer network proves beneficial. Comparative

106 economic assessment of centralized and decentralized systems may help in making informed

107   choices while designing urban sewerage systems and such studies have been carried out by

108   Woods et al. (2013), Eggimann, Truffer, and Maurer (2015), Jung, Narayanan, and Cheng

109   (2018) etc. However, there is no consensus among these studies; hence, there is a need for

110   increased research advocating for the need to frame revised design guidelines in this regard.

111   Eggimann, Truffer, and Maurer (2015) have performed a study based on modeling the

112   optimal degree of centralization for sewerage systems with a focus on cost minimization using

113   a planning tool based on the shortest pathfinding approach and clustering algorithms. The study

114   found that the optimal degree of centralization decreased with increasing topographical

115   complexities and dispersed or less dense settlements. Also, such a model is difficult to

116   implement on the ground since sewer network design depends on various dynamic processes

117   and variables such as population trends and settlement patterns. Hence, such an approach

118   requires more context-specific understanding making this kind of data-dependent model

119   challenging to implement in developing nations such as India due to data insufficiency and the

120   organic growth of urban centres.

121   In their study, Jung, Narayanan, and Cheng (2018) focused on a cost comparison between

122   the centralized and decentralized sewerage systems. The centralized system was designed for

123   the Alibaug region in India according to the Central Public Health and Environmental

124   Engineering Organization (CPHEEO)'s Manual on Sewerage and Sewage Treatment Systems.

125   For the decentralized systems, a three-step simulation model was used for testing various

126   configurations and cluster layouts of sewerage systems. The simulations included randomized

127   STP allocation, cluster formation using sewer path optimization, and simplified sewer design,

128   which was followed by cost calculation in terms of present value. The results showed that the

129   large-clustered decentralized models had relatively lower O&M costs but a higher capital cost

130   and land requirement when compared to the centralized system (Jung, Narayanan, and Cheng

131   2018). However, such modeling approach does not consider the ground complexities in urban

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132　areas which include the physical constraints such as topographical variations, high water tables,

133　rocky soil conditions and the socio-political constraints. The comparative assessments need to

134　consider the ground reality and local context for analyzing decentralized models in research

135　studies to get more accurate results.

136　　　　Hence, the present study aims to evaluate the economic feasibility of a decentralized

137　sewerage system as a potential alternative to the conventional centralized sewerage system in

138　urban areas, focusing on water reuse opportunities. The study also generates outputs and

139　learnings for other cities facing similar issues related to centralized sewerage systems. A large

140　Indian city with population exceeding one million has been considered for understanding the

141　ground issues in the sewerage systems at the urban level and conducting further study.

142　**COMPARISON OF CENTRALIZED AND DECENTRALIZED SEWERAGE**

143　**SYSTEMS**

144　　　　Centralized sewerage systems are the conventional means of sewage collection and

145　transport. The entire area's wastewater is transported mostly via gravity flow to a remotely

146　located sewage treatment unit in such a system. Various factors, such as population projections

147　and growing per capita water needs, are also considered while designing the centralized

148　systems (Bernal et al. 2012). The concept of using a fully-networked sewerage system comes

149　from the United States and Europe, where this system was first introduced to cater to the

150　increasing wastewater loads due to urbanization as well as to lower the incidences of diseases

151　arising out of unhygienic conditions and direct exposure to waste (Burian et al. 2000;

152　Hophmayer-Tokich 2006).

153　　　　Decentralized sewerage systems involve the collection, transportation, treatment, and

154　disposal or reuse of wastewater at or near the point of waste generation (CPHEEO 2013). On-

155　site treatment systems with the treatment unit located within the site of wastewater generation

156　itself are commonly known as decentralized treatment systems. This system is a historical

157   method of wastewater management practiced even before the introduction of centralized

158   systems in many geographies across the globe (Burian et al. 2000; Hophmayer-Tokich 2006).

159   However, multiple sewage treatment plants implemented at varying scales and catering to part

160   of the population load of a city or town are also known as decentralized treatment systems.

161   Recently, decentralized systems are becoming popular as a possible alternative to conventional

162   centralized sewerage systems. Many researchers are exploring the novel approach of

163   optimizing the decentralization scale that can fetch the maximum benefits from the

164   decentralized sewerage systems (Eggimann, Truffer, and Maurer 2015; Jung, Narayanan, and

165   Cheng 2018). Such a scaled approach for decentralization can overcome the limitations of

166   centralized and decentralized systems and provide higher sustainability and resilience to the

167   infrastructure.

168   **Centralized systems - Advantages and disadvantages**

169   Centralized systems have continued to be in use over the years due to many reasons, but

170   it has been realized lately that the O&M costs of these systems are high (Jung, Narayanan, and

171   Cheng 2018). Additionally, the process of renewing or upgrading the collection system after it

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

173   The limited availability of financial resources in many urban areas, especially in

174   developing nations, makes centralized systems the first choice among engineers (N. K. Singh,

175   Kazmi, and Starkl 2015). Furthermore, the easiness of planning and implementing large-scale

176   centralized treatment systems is another reason for its popularity among engineers. This also

177   fits well with the political goals of the prevailing politicians to announce large investments in

178   treatment infrastructure.

179   Amidst the scenario of scarce land in the core city, the centralized treatment plants are

180   usually located on a single large piece of land away from the main urban center. This also

181   addresses the social unacceptance of the provision of a treatment unit in the residential vicinity.

182 However, the control of the treatment systems and their O&M is affected due to limited

183 accessibility given its isolated location (Bernal et al. 2012).

184   When accounting for wastewater quality in centralized systems, there is non-uniformity

185 in the composition as the wastewater is received from different sources (Bernal et al. 2012).

186 This may become a burden on the treatment unit to maintain the sewage disposal standards.

187 Additionally, the redistribution of treated wastewater back to the city becomes highly

188 uneconomical as it is concentrated at a single point away from the city, resulting in a low water

189 reuse potential (Arceivala and Asolekar 2008; Ho and Anda 2006).

190   The concept of a centralized system has been derived from developed nations, where

191 there is high water consumption and adequate flushing velocity, which does not allow siltation

192 or choking in sewers. However, this concept is not necessarily suitable in the context of

193 developing countries having low and intermittent water supply, causing the problem of

194 sedimentation in sewers (CPHEEO 2013; Sitzenfrei and Rauch 2014). The developing nations

195 undergo uncontrolled urbanization resulting in the growth of unplanned settlements with non-

196 uniform densities. Adopting centralized systems for conveying the wastewater to larger

197 distances escalates the network costs in such conditions. Additionally, centralized treatment

198 systems are highly dependent on the power supply for their operation and the availability of

199 electricity for their smooth functioning can be affected by any economic or political issues

200 (Bakir 2001; Libralato, Volpi Ghirardini, and Avezzù 2012).The urban characteristics of

201 settlements, such as population density, land topography, building density, and land occupation

202 determine the favourability of centralized networks (Roux et al. 2011). These systems can work

203 well for the developed and densely populated areas of any settlement, for instance, the

204 residential and commercial centers or the densely packed core areas.

Decentralized systems - Advantages and disadvantages

The decentralized models provide effective solutions for wastewater management in smaller communities and peri-urban settlements. They require a relatively low budget and also provide opportunities for water reuse without excessive expenditure on water supply infrastructure (Bakir 2001; Massoud, Tarhini, and Nasr 2009; Nanninga et al. 2012; Wang 2014). Factors such as large elevation differences, inadequate existing capacities, demand at the periphery, and lower discount rates favour this system (Woods et al. 2013). When targeting the 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, Narayanan, and Cheng 2018; Woods et al. 2013). The water reuse opportunities can be seen in landscape and agriculture (parks, gardens, green belts, crops, etc.), environment (surface water bodies), non-potable urban uses (toilet flushing, washing, fire-fighting, etc.), and non-potable 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, Narayanan, and Cheng 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 centralized systems. However, the sewer capital costs and the O&M costs are much lower for decentralized systems (Jung, Narayanan, and Cheng 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 non-mechanized sewage treatment technologies such as ponds, constructed wetlands, etc. These systems can further lower the O&M costs as they don't require power and are easy to operate and maintain (Arceivala and Asolekar 2008; Kamal et al. 2008).. The land

230 requirement for decentralized systems is much higher or sometimes even twice (Jung,

231 Narayanan, and Cheng 2018) than the land requirement in centralized systems. Due to the

232 odour and noise issues, the public acceptance towards setting up sewage treatment units in the

233 vicinity of residential areas is not very optimistic.

234 The effective execution of decentralized systems faces governance challenges such as

235 generating revenue for operating the increased number of STPs, ensuring the compliance of

236 effluent with guidelines etc. As decentralized systems are gaining popularity, private service

237 providers have emerged to implement decentralized technologies. However, most of the

238 systems implemented in India do not comply with the effluent standards due to a lack of

239 suitable governance provisions (Reymond, Chandragiri, and Ulrich 2020). Further, there is a

240 shortage of incentives and budget allocation for improving urban sanitation services for the

241 poor, making it challenging to provide on-site systems. A holistic approach wherein the

242 government agencies proactively participate to ensure effective enforcement has to be adopted.

243 Active participation by various stakeholders, including government agencies, local bodies, and

244 the end customer, is required for better decision-making and infrastructure development at

245 household levels (Putri 2017). Hence, the decisions such as location for STPs, technology

246 selection should be taken by the urban local bodies after consultation with relevant

247 stakeholders. This will ensure the sustenance of the sewerage infrastructure.

248 Table 1 briefly compares the centralized and decentralized systems based on economic,

249 social, environmental, technical, governance and urban settlement characteristics. An

250 elaborated version of the same is presented in the Table S1 in SI. In summary, decentralized

251 systems might not be preferable over a centralized system in areas with high population density

252 and an already existing sewer system. Thus, adopting both systems at different locations as per

253 site-specific conditions could be a better choice rather than preferring one over another.
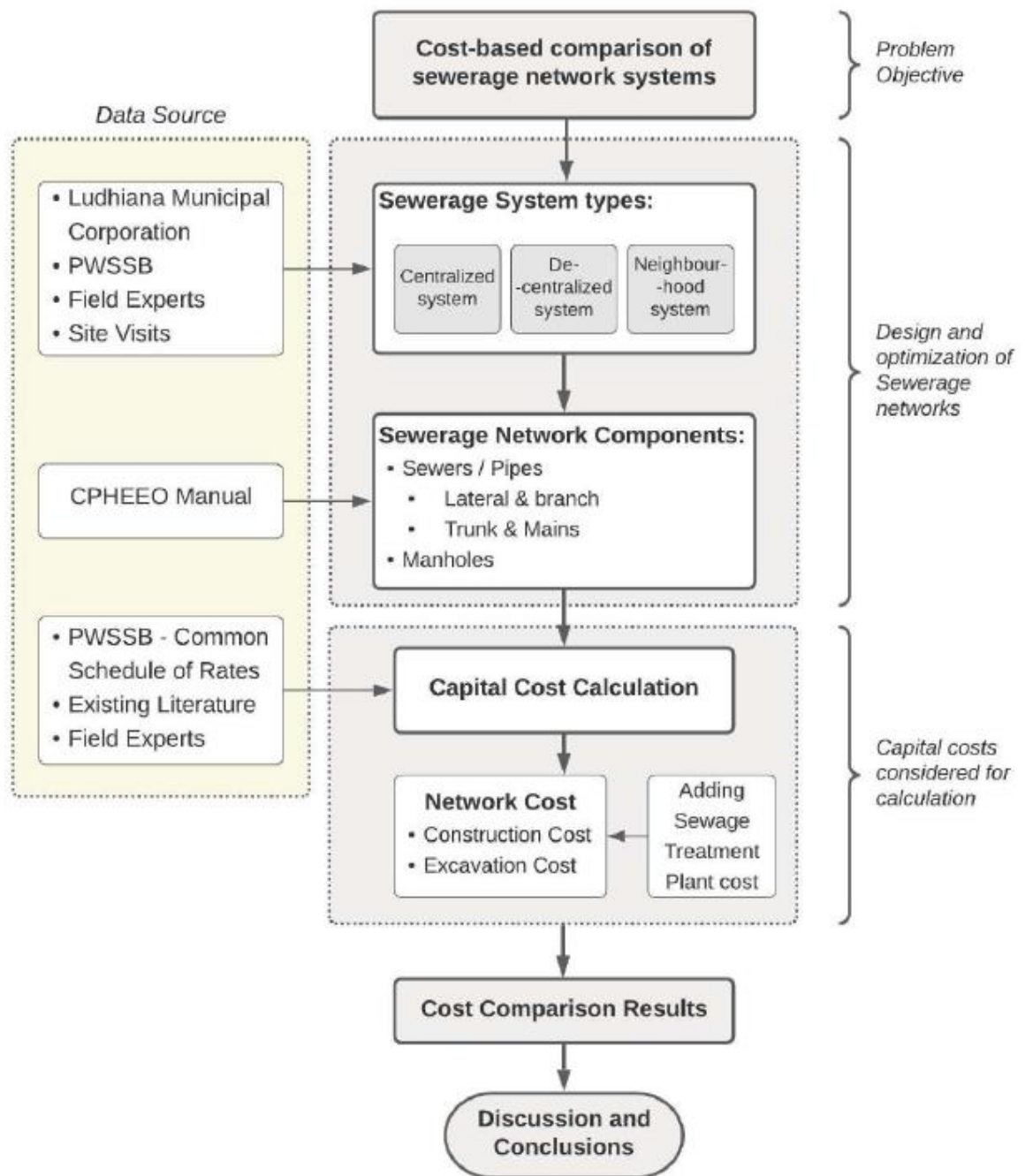
254 <Table 1 near here>

METHODOLOGY

The methodology adopted for conducting the study is depicted in a flowchart in Fig. 1. The objective of this research is the 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 neighbourhood networks, each catering to a part population load. Sewer pipes and manholes were the two main network 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 MS Excel.

The network design and optimization were performed using data on the existing sewerage system of Ludhiana city 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 get the cost comparison results, followed by discussion and conclusions.

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

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

282   manholes) along with the treatment cost, which was sourced from literature and field experts.

283   The final step of the study involved the economic comparison of the costs calculated for both

284   networks.

Study Area

286   Ludhiana, a city in North India, was chosen as the study area for conducting the

287   comparative analysis between centralized and decentralized systems. The city is an industrial

288   hub in the state of Punjab, spread across an area of 159 sq. km with a population of 16 lakhs

289   approximately, and contributes significantly to the state's economic growth. Although this city

290   provides for a suitable business environment, it has developed various environmental issues

291   due to rapid urbanization and industrialization.

292   Ludhiana follows a centralized sewerage system model for wastewater collection. The

293   city has been segregated into three sewerage zones according to the areas served by the three

294   STPs. The wastewater collected in each zone is conveyed to three STPs situated at different

295   locations outside the city's Municipal Corporation limits, as shown in Fig. 2.
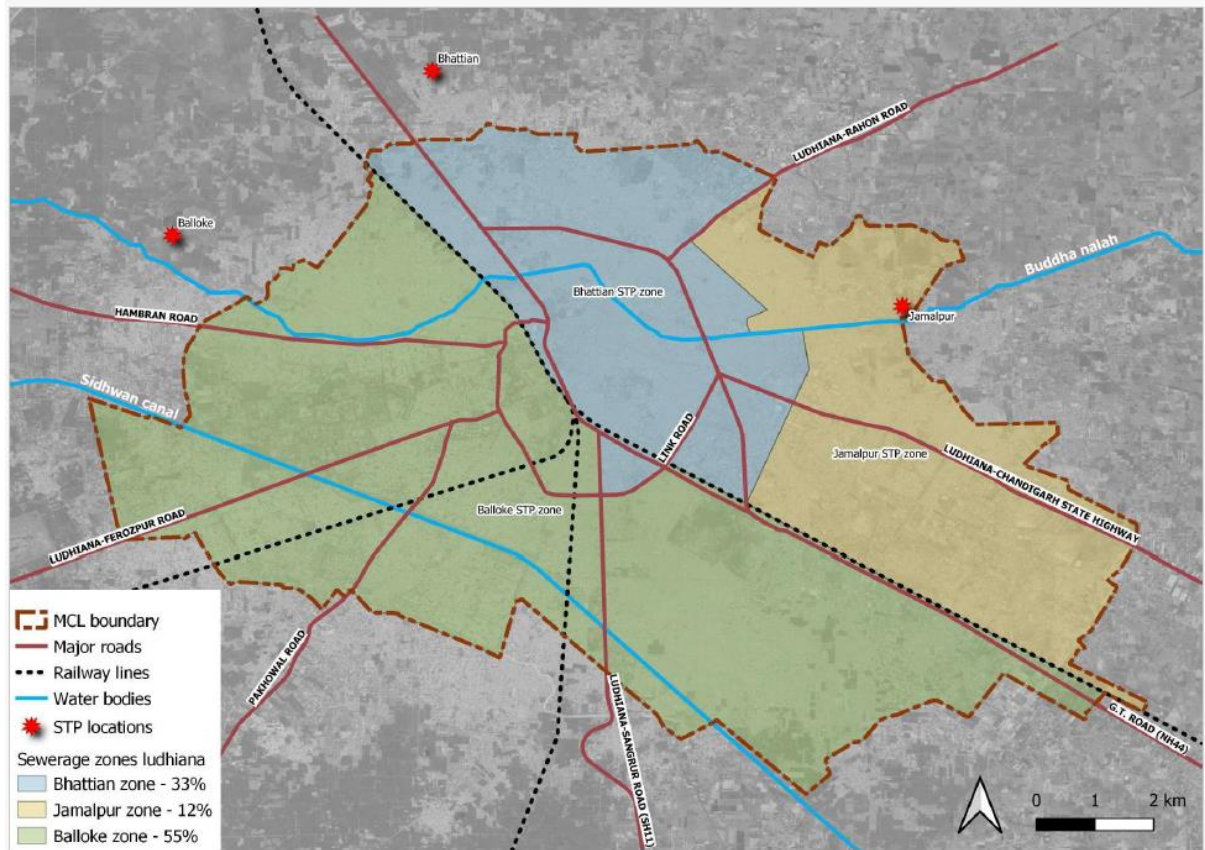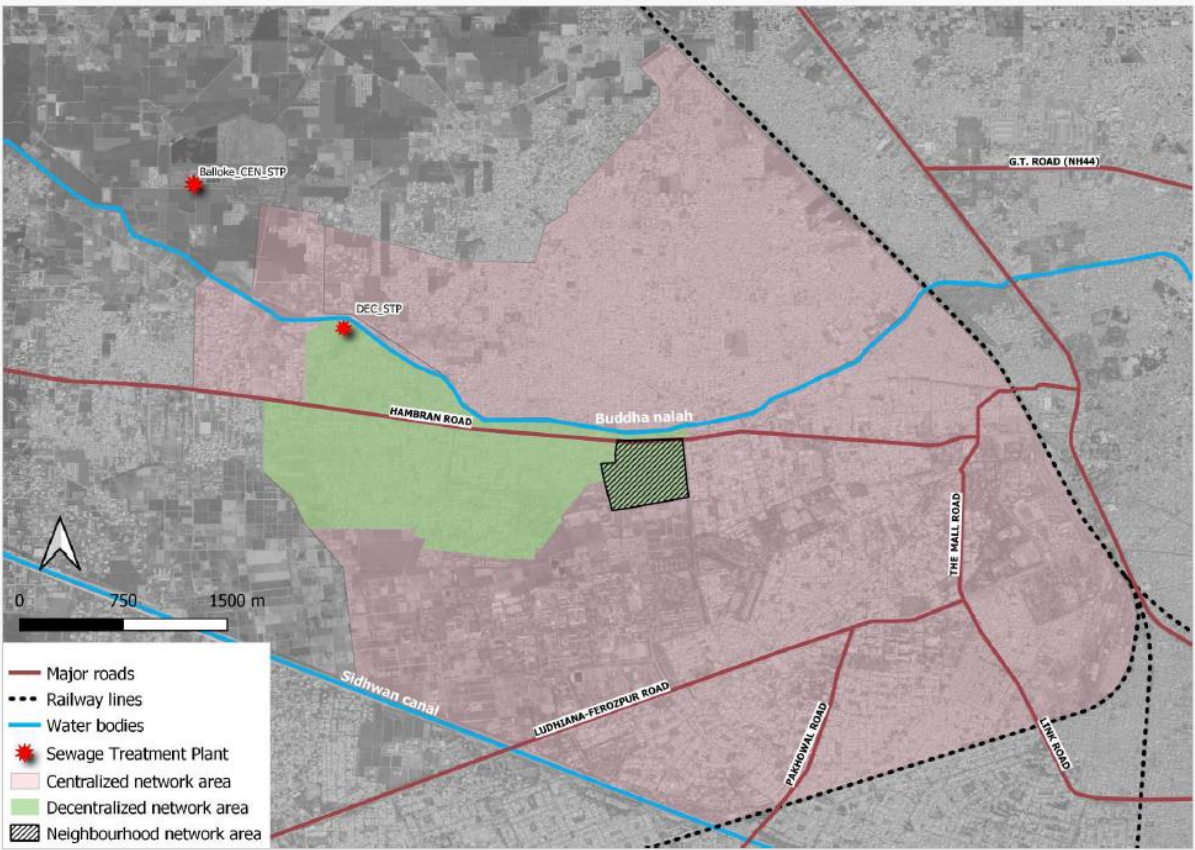
Fig. 2: Sewerage zones of Ludhiana

The sewerage system includes a hierarchical network of lateral pipes connecting to the households, sub-main 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-

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310   cleaning velocity. Also, the capacities of sewers are inadequate and overloaded due to

311   stormwater entering the network. In addition, the city does not have many provisions for

312   stormwater drainage. Only 11% of the entire city area is covered by the stormwater network

313   that has not been upgraded or supplemented after 2002 (CDP 2007; PUDA 2011).

314   Scenarios

315   The sewerage systems were selected at three scales: the centralized and decentralized,

316   and neighbourhood levels, as shown in Fig. 3. Both the systems were located in the existing

317   Balloke sewerage zone of the city, served by the Balloke STP. The centralized system covered

318   the largest area and was connected to the remotely located Balloke treatment unit in the city's

319   outskirts. For the comparative purpose in this study, the decentralized system was selected

320   within the area demarcated for the centralized area and is $1/7.5^{th}$ of the centralized system's

321   area. Similarly, the neighbourhood network has been considered within the decentralized area

322   and is $1/12^{th}$ of the decentralized system's area.

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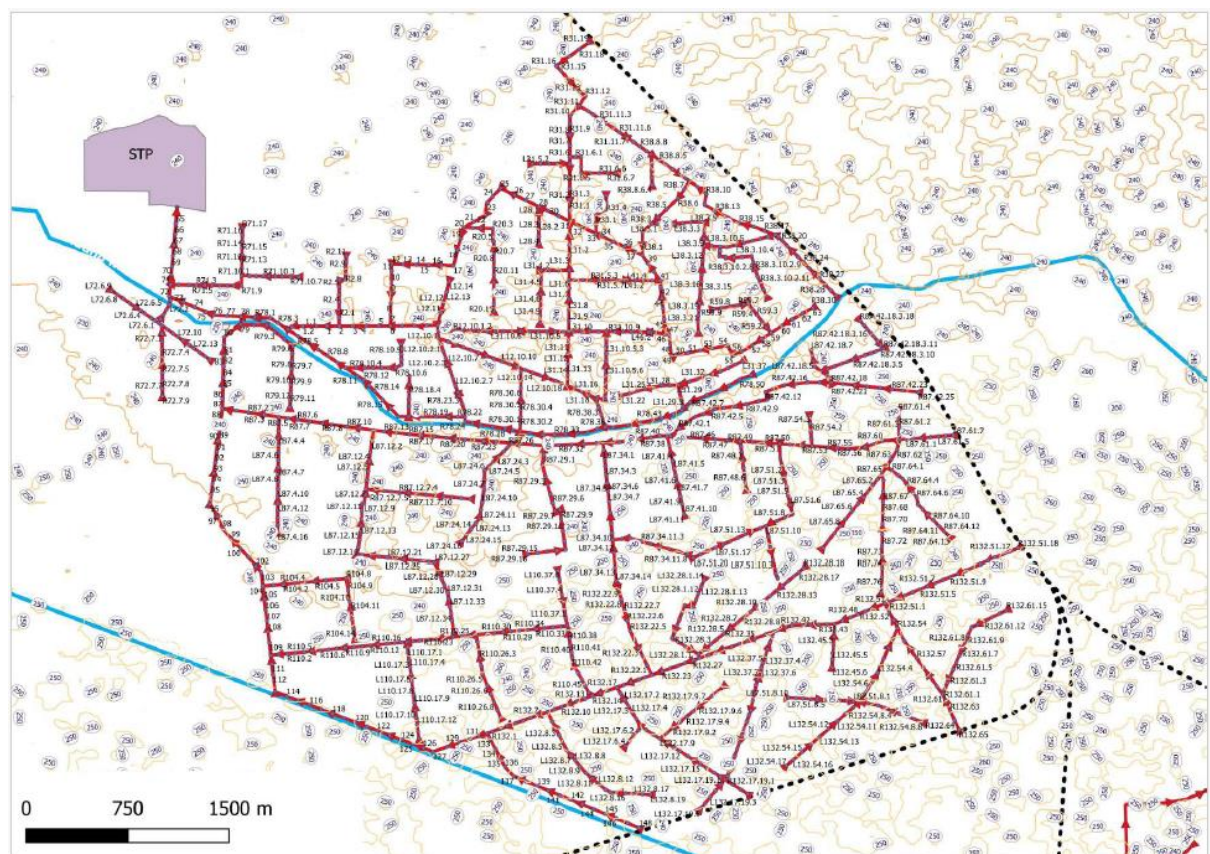**Fig. 3.** Selected scenarios with their treatment plant locations

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.

<Table 2 near here>

A third scenario called the neighbourhood 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 get the total network costs.

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336 • **Centralized system**

337   The Balloke sewerage zone was considered for selecting the centralized area in the city,

338 which is spread over 55% of the city's total area (88 sq. km). Since this is a considerably large

339 area for redesigning the sewer network system, a smaller part of this area was defined by

340 identifying physical boundaries within this sewerage zone and was isolated for carrying out the

341 study. The selected zone for the centralized network system as shown in Fig. 4 covered an area

342 of 4.7 km^2. Considering a standard population density of 15000 people per km^2, the population

343 for this area was estimated to be around 4,13,240. The water supply for this area was considered

344 as 220 Litres Per Capita per Day (LPCD), which is the average water supply rate for Ludhiana

345 city (PUDA, 2011). According to this, the total water supply demand for the area's residing

346 population is calculated to be around 90.9 Million Litres Day (MLD). The CPHEEO manual

347 (CPHEEO 2013) suggests that wastewater generation be taken as 80 percent of the water

348 supply. Therefore, the total wastewater generation for the selected area was estimated to be

349 72.7 MLD. So, the treatment plant for this area shall have the capacity to treat 72.7 MLD of

350 wastewater. The topography for this area is primarily flat with a gentle slope in the northwest

351 direction (refer to Fig. S1 in SI). The ground elevation levels range from 248 meters to 236

352 meters which were adopted from the DEM data provided by USGS Earth explorer (USGS

353 2020). The existing topographical situation in this area indicates that the existing location of

354 the Balloke STP is suitable for the treatment plant. Hence the existing location of STP was

355 retained.

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Fig. 4. Layout of designed centralized sewerage network

- **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 wards number 55 and 28 of the city. The topography for this area is mostly flat, with a gentle slope towards the northwest direction (refer to Fig. S2 in SI). The ground elevation levels range from 244 meters to 233 meters, as adopted from the DEM data provided by USGS (USGS 2020). Analyzing the existing topography of the study area suggests that the Haibowal Dairy Complex area, which is situated towards the northwest lower part of this area as a potential location for the treatment plant. The availability of vacant land in the dairy complex further supports this choice of location.

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Fig. 5. Layout of designed decentralized sewerage network

Neighbourhood system

A neighbourhood-level network was designed to calculate the cost of lateral and branch sewer pipes for 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 neighbourhood network has then been used for calculating the cost of the lateral and branch sewers.

As the name suggests, this area is considered at a neighbourhood level consisting of planned colonies. The selected area was located within the decentralized area boundary. The neighbourhood 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 neighbourhood network

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382   were defined by the surrounding secondary and tertiary roads. Since this is a small area, the

383   topography is mostly flat with a very gentle slope in the northwest direction (refer to Fig. S3).

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385

386   **Fig. 6.** Neighbourhood case-I sewerage network layout

387   The complete network was designed considering that it has to join one of the main sewer

388   lines of the decentralized and centralized network. The network comprises only the lateral and

389   branch links laid out along the tertiary roads of the selected zone. The sewer links between

390   manhole numbers 0 to 11 have just been considered for preparing the layout to join it with the

391   main link (refer to Fig. 6). However, the main sewer costs have not been counted for the

392   network specifications and cost calculations to avoid double-counting when extrapolated for a

393   larger area.

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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, etc. Once the sewer network layout was finalized, then 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 Central Public Health and Environmental Engineering Organization (CPHEEO 2013) to design and construct sewers. The network layout was finalized in QGIS, which is 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, etc. 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.

<Table 3 near here>

Cost analysis

The economic evaluation of the selected sewerage network systems was limited to capital cost calculation. The data for capital cost calculation was sourced from the Common Schedule of Rates provided by the Punjab Water Supply and Sewerage Board (PWSSB 2014). The total cost includes 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:

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418   • The cost of the neighbourhood network was extrapolated for both decentralized and

419   centralized scales separately to compute the cost share of lateral and branch networks in these

420   systems, which had not been included otherwise.

421   • The cost of the decentralized network was extrapolated for the centralized scale using

422   the area as an extrapolation factor.

423   • The cost of the treatment unit was added to the network cost calculations for computing

424   the capital cost of the total system. The treatment costs for both systems were considered in

425   terms of INR per MLD of the wastewater discharge under the condition of achieving the full

426   scale of economy, which was sourced from the literature and field experts (S. Singh and Gupta

427   2018; N. K. Singh, Banyal, and Kazmi 2016). The capital cost of the STP for the centralized

428   area is considered as 6 Million INR per MLD, whereas the capital cost of the STP for the

429   decentralized area is considered as 8 Million INR per MLD. The higher cost reflects the

430   reduced scale of the economy for capital costs in decentralized systems.

431   **RESULTS AND DISCUSSION**

432   The cost comparison results of the three systems have been described in this section along with

433   the discussion on the additional benefits offered by the decentralized systems. Further, a

434   planning model for the holistic implementation of the three systems in an urban area has also

435   been presented. Lastly, the limitations of the present work along with the scope of future works

436   have been discussed.

437   **Economic comparison**

438   The total capital costs of centralized and decentralized networks, which include costs

439   related to sewer pipes, excavation, laying of pipes, manholes, and STP, are shown in Table 4.

440   The economic comparison shows that the centralized and decentralized collection systems have

441   almost similar equivalent capital expenditures for Ludhiana. The cost trends were also

442　　compared for different cost components i.e., sewer pipe costs versus excavation costs and total

443　　sewer pipe costs versus total manholes costs for both centralized and decentralized systems,

444　　which did not show any significant cost differences either (as shown in Fig.7). Interestingly,

445　　this analysis shows that the sewer cost is 1.7 times higher than the excavation cost and about

446　　2.6 times the manholes costs, respectively. This signifies the importance of reconsidering the

447　　network length while planning sewerage infrastructure. The network costs for both centralized

448　　and decentralized networks are calculated as INR 0.467 million/ha. The results will be similar

449　　for other cities with a flat topography; however, these results might vary in case of different

450　　topographies.

451　　　　　　　　　　　　　　　　　　　<Table 4 near here>

452　　　　　　Several studies have compared the costs of centralized and decentralized networks. Few

453　　studies have suggested that decentralized systems are more cost-efficient for sparsely populated

454　　areas, while conventional (centralized) systems might be less capital-intensive for densely

455　　populated and well-developed areas (Bakir 2001). However, results from the current study on

456　　Ludhiana present a different outcome where the capital costs for both systems are comparable

457　　for a population density of 150 people per hectare in a well-developed urban area. This result

458　　signifies the critical role of O&M costs of treatment systems while planning the sewerage

459　　infrastructure of a given city. In developing countries such as India, capital costs are usually

460　　sourced through national schemes or funding by international organizations. In this scenario,

461　　the consideration of O&M costs in decision-making gains prominence. This aspect is also

462　　highlighted by Kalbar (2021a), wherein the role of O&M costs is shown to be dominant in the

463　　life cycle costing of wastewater treatment.

464　　　　　　Mara (2012) has reported that the conventional underground drainage systems become

465　　economical beyond 150 people per hectare. The difference in results can be credited to

23

466 parameters such as topographical variations, population density, urban form, and land use. For

467 example, Ho and Anda (2006) have highlighted the possibilities of diseconomy of scale in the

468 case of centralized systems if the sewage has to be pumped through long distances or there is

469 an excessive inlet of stormwater or wastewater into the sewerage system. Hence, the inclusion

470 of pumping stations and their associated costs might reflect different results from those

471 observed in this study, which considers an ideal gravity-flow scenario. This suggests that

472 considering the study area's topography while planning sewer network to utilizing gravity to

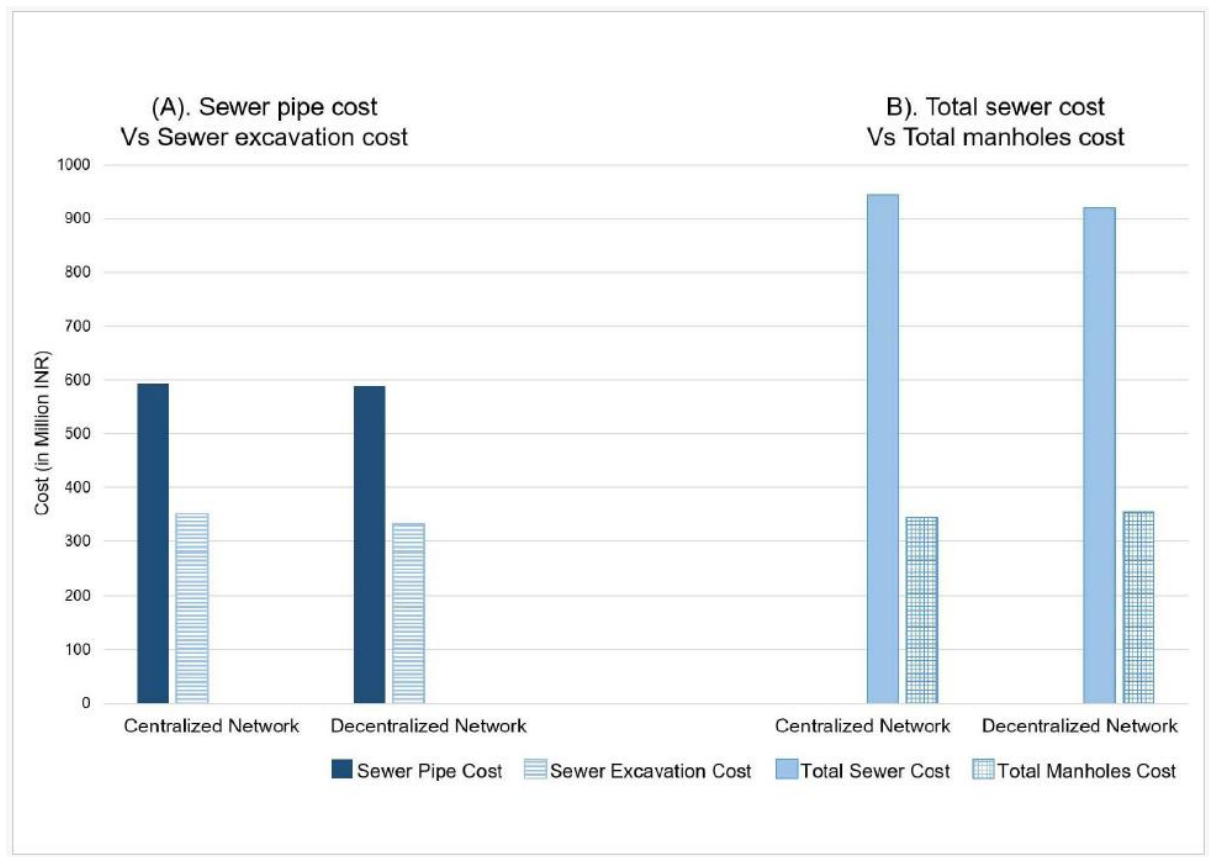473 the maximum possible extent, can create energy-efficient infrastructure.

474

475

476 **Fig. 7.** Cost comparison chart for (A). Sewer pipe cost vs. Sewer excavation cost and (B).

477 Total sewer cost vs. Total manholes cost

478   Other studies on similar topics have suggested that the initial capital investments for the

479 collection system of centralized systems are relatively higher than decentralized systems

24

480   (Libralato, Volpi Ghirardini, and Avezzù 2012; Roux et al. 2011). Studies have reported that

481   decentralized sewer capital costs are lower than centralized systems by 40-50 percent (Maurer,

482   Rothenberger, and Larsen 2005; Jung, Narayanan, and Cheng 2018). A study conducted by

483   Jung, Narayanan, and Cheng (2018) in Alibaug draws a cost comparison between centralized

484   wastewater management systems and cluster-type decentralized wastewater management

485   systems showing a difference of 40-45 percent in the cost of decentralized systems as compared

486   to centralized systems. The observations from the above-mentioned studies contradict the

487   results from our study, which do not show significant differences in the costs of the three

488   systems. This variation can be explained by the fact that the cost of sewerage systems varies

489   significantly with contextual characteristics such as land topography, population density,

490   wastewater loads, etc.

491   Further, in the present work, the cost of sewer pipes is found to have a higher impact on

492   the total sewer cost than its excavation cost. A comparison between the total sewer cost and

493   the total manhole cost shows that the sewer cost has a higher impact on the overall network

494   cost. It can therefore be inferred that optimizing the sewer pipe cost according to various

495   parameters such as the material selection, sizes, depths, and design lifespan might help

496   considerably reduce the overall collection system costs. The study by Eggimann, Truffer, and

497   Maurer (2015) models the optimal degree of centralization for sewerage systems, but does not

498   include manholes in the sewer design and cost computation. Our study shows that manholes

499   are an integral component of the sewerage network system, which holds a considerable share

500   in the total cost of the network system and should also be accounted in economic assessment.

501   The depth of sewers increases with increased network length in a centralized system, more

502   often in flat terrains. In such situations, the construction of manholes at higher depths is

503   required implying higher costs. However, decentralized systems require a shorter sewer

25

504 network which is also laid at relatively shallower depths, thereby reducing the cost component

505 of manholes.

Other benefits of decentralized systems

507   The capital cost of decentralized systems was nearly similar when compared to the

508 centralized system costs in this study. However, decentralized systems offer additional benefits

509 that cannot be readily measured. Firstly, they provide water recycling and reuse opportunities

510 for various urban uses such as landscaping and agriculture, non-potable domestic and industrial

511 uses, and replenishing surface water, thereby reducing the load on water supply infrastructure

512 and also promoting a circular economy (Arceivala and Asolekar, 2008; Ho and Anda, 2006;

513 Kakwani and Kalbar 2020). Secondly, the effort for planning, designing and implementing

514 decentralized systems is lower than conventional centralized systems. Decentralized systems

515 allow for phased investments, thus reducing investment loads in the municipal authorities

516 (Jung, Narayanan, and Cheng 2018). This can also cater to uncertain and dynamic factors such

517 as population growth and changing land-use patterns. Thirdly, the environmental benefits of

518 these systems outweigh their costs, as they have a higher potential for achieving environmental

519 sustainability (Liang and Dijk, 2008; Ho and Anda, 2006), which can help the urban local

520 bodies attain sustainable development goals. Further, natural treatment systems such as

521 constructed wetlands having enormous economic and environmental benefits can be

522 conveniently implemented in a decentralized manner. Centralized systems, however adopt the

523 conventional mechanized treatment systems that pose operational problems in the long run.

524 Considering the techno-economic and environmental sustainability, Kalbar (2021b) has

525 identified the approach of hybrid wastewater treatment systems (defined as the strategic

526 integration of mechanized and non-mechanized/ natural treatment systems) as a better

527 alternative in land-constrained areas than the mechanized or natural systems implemented in

528 isolation. Fourthly, a decentralized system can offer higher energy efficiency than centralized

26

529 systems because they do not require the installation of pumping stations used to prevent deep

530 excavations in the case of centralized systems.

531   Additionally, greater system resilience and adaptability are also offered by the

532 decentralized systems such as lower vulnerability, reduced failure risks, higher recovery due

533 to power cuts, and improper maintenance, as the risk is distributed across multiple smaller

534 systems (Bernal et al. 2012; Dahlgren et al. 2013; Jung, Narayanan, and Cheng 2018; Leigh

535 and Lee 2019). Also, decentralized systems are capable of responding to changing goals of

536 wastewater treatment, making them more flexible compared to centralized systems (Spiller et

537 al. 2015). Lastly, the decentralized systems can ensure maximum economic benefits and a

538 larger market for recycled water use if optimized in terms of the degree or scale of the

539 decentralization.

540 **Learnings for other cities in India**

541   The present study suggests that both centralized and decentralized systems have certain

542 advantages and disadvantages from different aspects. A holistic approach can be adopted to

543 obtain maximum benefits from these systems and reach an optimized solution for

544 infrastructural planning in urban areas. Planning guidelines can be framed according to the

545 compatibility of each system. A basic model proposed in Fig. 8, presents the idea of

546 implementing different systems in combination depending on the local urban characteristics.

547   Most cities, especially in India, grow outwards from a dense core area. The population

548 density is found to be lower in the outer areas surrounding the central core of the city

549 (Mookherjee 2004; Mondal and Banerjee 2021). A study by Kotharkar and Bahadure (2020)

550 examined the changes in the spatial distribution of built-up areas and population densities in

551 the core urban zone, intermediate zone, and peripheral zone of eight selected Indian million-

552 plus cities. They reported that the population densities decrease from the urban core to the

553   peripheral parts of the cities and vary in the range of 150-400 person per hector (pph) for the

554   urban core, 60-200 pph for the intermediate zone, and 10-60 pph for the peripheral zone for the

555   selected eight cities as per the population data for 2010. Considering this growth pattern, the

556   cities can be divided into three zones- a highly developed dense urban core area (Zone 1),

557   surrounded by a lesser densely populated immediate extension of the core area (Zone 2), and

558   finally a peripheral area that is sparsely populated and of low density (Zone 3). Sewerage

559   systems can be provided considering the varying densities in the urban areas such that:

560   • The core areas of the city that are generally highly developed and densely populated

561   can be covered with a gravity-flow underground network connected to a wastewater treatment

562   unit.

563   • The extension area surrounding the dense core areas in a town is generally found to be

564   undergoing development but has comparatively less dense population as compared to the city

565   cores. So, these areas can be provided with a system of individual septic tanks connected to a

566   network of open drains. When these areas undergo complete development in the future, they

567   can be connected to the underground network existing in the core areas or provided with
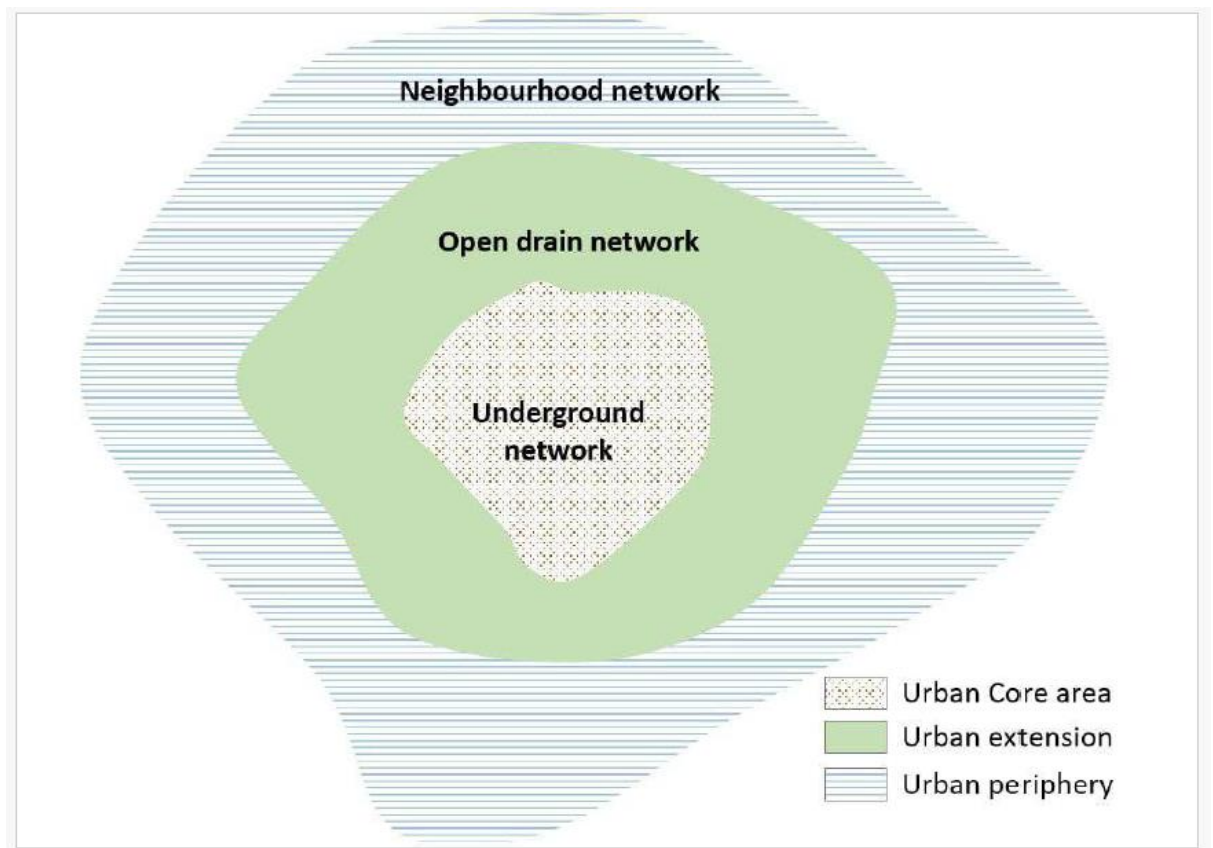
568   separate treatment systems.

569

570

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), Zone 3- Urban periphery (low density)

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 neighbourhood 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 the economic assessment of the selected sewerage systems. Under the economic aspect, only the 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

29

584   by replicating similar studies in other cases with different contexts such as varying population

585   density, different topographic conditions, urban form, which will significantly contribute to

586   this research area. Optimizing the degree of decentralization is another novel concept that can

587   be explored as a part of future research work. This study has not considered the environmental,

588   social, governance aspects, which are becoming essential to assess the sewerage systems based

589   on a holistic perspective.

590   The authorities frame the current guidelines on sewerage network design with a focus on

591   the application of centralized systems only, which should also be extended to decentralized

592   systems for better choices. The optimum scale of decentralization is an important area that

593   needs further exploration for deriving the best decision outputs for various contexts, as the

594   economic impacts of these sewerage systems vary contextually.

595   **CONCLUSIONS**

596   Cities are experiencing growing challenges of freshwater scarcity, wastewater

597   recycling, sustainable development goals and emerging challenges due to climate extremes.

598   This demands for sustainable and resilient infrastructure which can be achieved using

599   decentralized infrastructure planning as it offers multiple environmental, economic and social

600   benefits. The present study has assessed capital costs for the centralized and decentralized

601   systems based on a detailed sewer design in a real-life case study from India. The results have

602   shown that the costs of both sewerage network systems (at different scales) are almost the same

603   for the chosen case, with a population density of 150 people/hectare and a gently sloping

604   topography. As the capital costs for the systems were comparable, the focus of decision-making

605   should be on the O&M costs, and further research should explore the life-cycle costs of the

606   sewerage infrastructure. Also, awareness generation regarding the other non-tangible

607   environmental and social benefits of decentralized systems should be carried out among urban

608   local bodies. For example, a decentralized infrastructure is more resilient and can cope with

609 climate extremes more effectively than centralized systems. Policy guidelines encouraging the

610 adoption of decentralized systems in various settings of urban, peri-urban and rural areas

611 should be framed. Further, the analysis should be extended from a gently sloping topography

612 to hilly and undulating terrains and for varying population densities to understand the role of

613 urban settlement characteristics in the liquid waste management of a city.

614 The comparison of centralized and decentralized systems shows that both systems have

615 advantages and disadvantages. Hence, the scale of decentralization will play a key role in

616 attaining the benefits of both systems. The present work only represents two extremes of

617 centralized and decentralized systems; however, the methodology should be extended to

618 quantify an optimal scale of decentralized systems based on a multiple parameter-based sewer

619 design. At the same time, it should be realized that a one-size-fits-all approach is not applicable

620 to urban water infrastructure; hence case-specific decisions should be taken based on an in-

621 depth understanding of the local context. The urban local bodies need to understand the

622 significance of scale in implementing sewerage infrastructure and should analyze the local

623 geographic and economic dimensions before planning sewerage infrastructure. Such a holistic

624 planning and design approach will help attain sustainable liquid waste management.

637   **Disclaimer**

638   The authors declare that they have no known competing financial interests or personal

639   relationships that could have appeared to influence the work reported in this paper.

640   **SUPPLEMENTARY MATERIALS**

641   *Online*

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788

789   **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 to decentralized	Higher as compared to 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 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 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 up-gradation	Potential for technological innovations due to its shorter design period
O&M effort	Less number of skilled/high-skilled resources needed	Facilitate semi-skilled/ unskilled workforce
System resilience	Failure in the treatment plant affects the complete network	Failure risk lowered due to staggered systems
Wastewater uniformity	Relatively non-uniform composition	Relatively uniform composition
Governance		
Policies/guidelines	Readily available design guidelines	Need for detailed guidelines and policies
Control	Better control due to single unit	Loss of control due to multiple plants
Urban Settlement Characteristics		
Population density	Suitable for 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

790

791 **Table 2.** Specifications of the selected three scenarios

S.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	2754.9	413000	90.8	72.7
2.	Decentralized	363.77	54566	12	9.6
3.	Neighbourhood	30.3	4548	10	0.8

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

Sr. No.	Factors	Centralized	Decentralized	Neighbourhood
1.	Population density	150 people/ha	150 people/ha	150 people/ha
2.	Infiltration rate	5000 liters/ha/day	5000 litres/ha/day	5000 liters/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 meters
7.	Sewer length	85130.23 m	11009.04 m	5733.10 m
8.	Number of Manholes	1289	250	201

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795 **Table 4.** Total costs of the sewerage systems

Type of sewerage system	Total Sewerage Network Cost	STP Cost (in Millions)	Total system cost

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	(in Million INR)	Capacity (MLD)	Number of STPs required for covering the entire area	Cost (Millions per MLD)	Total STP cost (in Million INR)	(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**

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