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Adapting sanitation systems to demographic transitions: Optimizing hybrid configurations of sewered and non-sewered solutions

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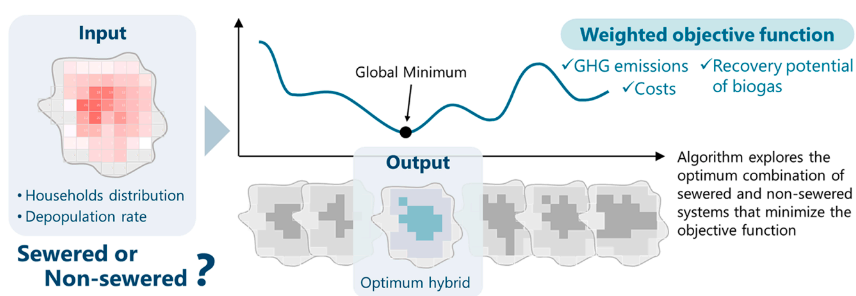
HIGHLIGHTS

- Population decline increases costs of maintaining sewered sanitation.
- Shifting to non-sewered *Johkasou* avoids long-term redundant investments.
- Mathematical optimization finds optimal hybrid sewered–non-sewered system.
- Hybrid sewer–*Johkasou* systems outperform single-technology options.
- The hybrid design minimizes 50-year costs and GHG emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Non-sewered sanitation systems play a vital role in achieving global sanitation goals by providing resource-efficient and flexible solutions, particularly in resource-constrained settings. When effectively integrated with infrastructure of centralized systems, they offer multiple advantages, including reduced asset redundancy, improved economic feasibility, intergenerational equity, and better public health outcomes—ultimately maximizing overall system performance. This study presents a novel multi-objective optimization framework that identifies the optimal spatial configuration of sewer-based system and the *Johkasou* system as a representative fully road-transported, non-sewered system, explicitly accounting for population decline and diverse performance criteria, including capital and operating costs, greenhouse gas (GHG) emissions, and biogas recovery potential. The optimization model integrates generalized objective functions for these performance criteria, all linked to spatial population dynamics. A case study showed that maintaining a centralized system alone increases both costs and GHG emissions over a 50-year horizon. In contrast, transitioning to an optimally hybridized sewered and non-sewered system configuration reduces expenditures and environmental impacts. Additional benefits are achieved through optimized onsite treatment technologies that reduce operational GHG emissions by 33 %, and through efficient sludge collection. The results demonstrate the superior performance of hybrid systems over single-technology approaches and emphasize their potential as smarter, more sustainable sanitation

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solutions in regions facing aging infrastructure and depopulation. Owing to its generic structure and interpretable outputs, the model is broadly applicable and adaptable to varying policy contexts, offering decision-makers a robust basis for designing sustainable, context-sensitive sanitation strategies.

1. Introduction

Conventional centralized wastewater systems are major infrastructure assets for many municipalities. According to the OECD (2024), over 80 % of the population in approximately half of the OECD member countries is currently connected to public sewage networks. However, many sewer pipelines have been in service for over 50 years, and as they age, the risk of deterioration increases, leading to growing rehabilitation demands over the coming decades (Laakso et al., 2019; Newton and Vanier, 2006). While conventional centralized wastewater systems have achieved substantial environmental benefits, their economic sustainability is increasingly uncertain, particularly in regions experiencing both population decline and infrastructure aging.

Population decline is a growing challenge in many aging cities, particularly in high- and middle-income countries, and it can result in a mismatch between conventional large-scale infrastructure and actual service demand (United Nations, 2024). In Japan, approximately 96 % of municipalities are projected to experience depopulation, and many already face difficulties maintaining infrastructure assets with less revenue and labor shortages (IPSS, 2023). Similar trends are observed globally, including in cities across the United States (Sutradhar et al., 2024) and rural regions of European counties (Hummel and Lux, 2024). In fact, >40 % of nearly 30,000 U.S. cities may face a 12–23 % population decline by 2100 (Sutradhar et al., 2024). If preservation investments are made to maintain sewer networks for a shrinking user base, cost recovery becomes increasingly difficult, leaving fewer residents to shoulder the financial burden. Sewer rehabilitation is particularly capital-intensive. For example, Cured-in-Place Pipe lining can cost from USD 30 to USD 700 per linear foot in some cases (GHD, 2022; Kaushal et al., 2022; SEKISUI SPR Americas, n.d.). Moreover, the cost-effectiveness of centralized sanitation systems is highly sensitive to population density. In sparsely populated areas with fewer than 1000 population equivalents (PE) per km^2, sewer construction cost can exceed USD 1500 per PE km^2, and operating costs follow similar trends, rendering the centralized system economically unfeasible (Saadatinavaz et al., 2024). Consequently, depopulating local governments maintain centralized systems with excess capacity and underutilized assets, making investments in sewer preservation potential sunk costs in the coming decades. Local governments must therefore adapt infrastructure and public services to the new demographic reality while remaining consistent with environmental objectives.

A smart and sustainable approach involves integrating various non-sewered sanitation systems – such as septic tanks and infiltration systems – into existing centralized wastewater treatment with sewer networks (sewered sanitation systems; SSS). A non-sewered sanitation system is a prefabricated integrated treatment unit, comprising toilet facility and treatment components that collect, convey, and fully treat the specific input within the system, and is not connected to a networked sewer or networked drainage systems (ISO, 2018). It is further categorized into “Mixed-transport systems”, “Source-separated mixed-transport”, and “fully road-transported systems”, based on the extent of reliance on pipe-based conveyance (Strande et al., 2023). Non-sewered sanitation systems are potentially resource efficient, as they do not require expensive sewer infrastructure, and therefore offer a viable alternative in areas where new construction or rehabilitation of aging centralized sewer networks is impractical or cost prohibitive. When a mega-centralized sewered system and a decentralized system capable of recovering resources including non-sewered systems are effectively integrated, this hybrid system can outperform conventional centralized models in terms of cost optimization, resource recovery, and climate resilience (Torre et al., 2021). In the context of shrinking societies, downsizing centralized systems becomes imperative, and hybrid solutions can be deployed and decommissioned more flexibly reducing the risk of infrastructure becoming underutilized. These considerations provide a compelling rationale for transitioning from centralized systems to appropriately scaled sewered and non-sewered hybrid configuration tailored to the demographic dynamics of shrinking urban areas.

Japan has adopted a fully road-transported non-sewered system called *Johkasou* system, since 1960s, especially in areas where sewer was not constructed due to geological or financial constraints. It consists of a wastewater treatment unit called *Johkasou*, a small-scale unit designed for the onsite blackwater and greywater treatment at household level, and offsite sludge treatment process involving scheduled sludge removal and road-based transportation (Endo and Koga, 2021; Strande, 2024). Owing to its lower capital cost and shorter infrastructure lifespan, the system is well suited to a shrinking society. Transitioning areas with declining populations from sewered systems to *Johkasou*, while maintaining the sewer systems in dense urban areas, can reduce the redundancy in the sewer network and minimize the long-term risk of unused infrastructure. Given the substantial capital investments required to maintain sewer infrastructure, the degree of sewer coverage is a critical factor that determines the efficiency of the hybrid system. Beyond economic considerations, such a shift in infrastructure will influence environmental impacts and resource recovery potential, which are key priorities in sanitation planning. Despite cost advantages, the *Johkasou* system may increase overall energy demand with potentially greater greenhouse gas emissions, as observed in other non-sewered systems (Hendrickson et al., 2015; Risch et al., 2021). *Johkasou* sludge has biogas recovery potential and can be co-digested with sewage sludge to increase total biogas amount from wastewater, although its biogas production potential is lower than that of untreated wastewater conveyed by sewer. To maximize overall system performance, these trade-offs between sewered system and *Johkasou* system must be carefully assessed, enabling the design of optimal spatial configurations that meet multiple viability criteria.

A recent model, *TURN-Sewers*, has introduced the ability to simulate infrastructure deterioration over time and optimize transitions between decentralized and centralized systems in response to urban expansion (Duque et al., 2024). However, the current version does not address the optimal integration of non-sewered and sewered systems in hybrid configurations. Moreover, decentralization in previous studies typically refers to community-scale sewered systems, with limited consideration of non-sewered systems that require sludge collection and transport (Huang et al., 2022; Jung et al., 2018). The potential benefits of sludge centralization for enhanced biogas recovery also remain largely overlooked. Notably, most existing models ignore demographic dynamics over the infrastructure life cycle, despite population density strongly influencing optimal centralization levels and total system costs (Eggimann et al., 2016; Kavvada et al., 2018). In summary, previous studies have not demonstrated how to design an optimal configuration of sewered and non-sewered systems while simultaneously addressing multiple performance criteria.

This study aims to develop a multi-objective optimization framework to determine the optimal spatial layout of integrated sewer and *Johkasou* system as a representative fully road-transported, non-sewered system, based on household distribution. The optimization model incorporates lifecycle costs, environmental footprints, and the potential for biogas, with the objectives of minimizing capital and operational expenditures, reducing greenhouse gas (GHG) emissions, and maximizing the volume of biogas recovered from sludge. Household spatial distribution is used as a key local-specific parameter, which simplifies model complexity and enhances practical applicability. In addition, demographic changes are explicitly integrated into the modelling framework to assess long-term system viability. These characteristics make this framework broadly applicable across various contexts, including scenarios of population growth. To our knowledge, this is the first study to derive an optimal hybrid layout of sewered and non-sewered sanitation systems using mathematical optimization while considering a range of factors beyond cost alone. The model is designed to be modular and extensible, allowing for adaptation to site-specific conditions and integration with other planning tools.

2. Methods

2.1. Sanitation service chain and scenario

We develop an optimization framework assuming that an aged centralized sewered system is either replaced with new sewer infrastructures or downsized to a non-sewered system. We focus particularly on sanitary sewers in fully separated sewer networks, which account for over 80 % of Japan's entire sewer infrastructure. When existing sewers are rehabilitated, aging pipes are replaced using the spiral-wound lining method (Ishmuratov et al., 2013). The existing wastewater treatment plant (WWTP) is assumed to have exceeded its standard lifetime and to be rehabilitated for continued operation over the next 50 years. If the system is downsized to a non-sewered system, the existing sewer connection is terminated and the *Johkasou* (Hereafter denoted as onsite treatment: OST) system is installed. Details of the *Johkasou* system are provided in Supplementary Information S1 and in Gaulke (2006).

Fig. 1 illustrates the sanitation service chain assumed in this study. Each household is connected to the sewer network or equipped with an OST plant. The treated effluent from OST plant is discharged into a nearby gutter and from there to the environment. Sludge generated from OST plant is periodically removed and transported a centralized sludge treatment facility through a planned collection scheme, enabling biogas recovery. In contrast, wastewater conveyed through sewers is treated via the activated sludge process or oxidation ditch method. Sludge from primary and secondary wastewater treatment, along with that from OST systems, is co-digested at the centralized facility. The biogas generated is utilized to offset the energy demands of the centralized treatment plant. This study did not perform a whole system comparison between sewered and non-sewered systems; rather, it focused specifically on the conveyance and treatment phases of wastewater and sludge in relation to service area and household density.

2.2. Multi-objective optimization model

2.2.1. Generalized formulation of performance indicators

Fig. 2 presents an overview of the optimization process developed in this study. The algorithm aims to identify the optimal spatial configuration of sewered and non-sewered sanitation systems that minimizes both economic costs and GHG emissions while maximizing biogas production through sludge digestion. Economic costs include both capital expenditures (Capex) and operational expenditures (Opex). For sewered system, Capex includes the rehabilitation costs of WWTP and sewer, while for non-sewered system, it includes OST plants, sludge vacuum trucks, and cars for routine maintenance of OST plants (Fig. S2). For sewered system, Opex include cleaning, investigation, and repair of sewer pipe, and chemicals and electricity cost for WWTP, while for non-sewered system, it accounts for labor and fuel associated with sludge collection and routine maintenance, as well as electricity consumption for blower aeration in the OST plant (Fig. S2). GHG emissions are calculated for phases of construction and operation (including methane and nitrous oxide from biological process), sludge transport, and indirect emissions from electricity usage (Fig. S3). Figs. S2 and S3 provide detailed process boundaries. The amount of biogas was calculated from the volume of excess sludge from WWTP and OST plants that are consolidated at a centralized sludge treatment plant, sludge characteristics including total solids and volatile suspended solids, and the conversion ratio of volatile suspended solids to methane (Section S3).

The number of served households determines the volume of wastewater and sludge, which in turn dictates the required infrastructure size and system performance. Based on this assumption, we formulate generalized performance indicators for both sewered and non-sewered systems as functions of service population and area. The derivations of these formula, including sewer network model and haulage distance models, are presented in the Supplementary Information, Sections S2 to S6. Table S1 presents the definitions and values of the model parameters used in this study.

2.2.2. Objective functions and constraints

The optimization is conducted in a virtual L^2 km^2 district, subdivided into k^2 km^2 grids. Each grid cell (i,j) $(i = 1, \cdots, L/k; j = 1, \cdots, L/k)$ is assigned a number of households $N_{i,j}$, and the total number of households is $N = \sum_{i=1}^{L/k} \sum_{j=1}^{L/k} N_{i,j}$.

The objective is to allocate either sewered or non-sewered system to each grid in a manner that minimizes total cost and GHG emissions, while maximizing centralized biogas recovery. The objective functions for each system are defined as the sum of generalized formula weighted by the unit prices as follows:

$$f_{SSS}(N_{SSS}) = C_{SSS_{capex}}(N_{SSS}) + C_{SSS_{opex}}(N_{SSS}) + w_{GHG}\left\{GHG_{SSS_{cap}}(N_{SSS}) + GHG_{SSS_{ope}}(N_{SSS})\right\} - w_{biogas}V_{SSS}(N_{SSS}), \quad (1)$$

$$f_{NSSS}(N_{NSSS}) = C_{NSSS_{capex}}(N_{NSSS}) + C_{NSSS_{opex}}(N_{NSSS}) + w_{GHG}\left\{GHG_{NSSS_{cap}}(N_{NSSS}) + GHG_{NSSS_{ope}}(N_{NSSS})\right\} - w_{biogas}V_{NSSS}(N_{NSSS}), \quad (2)$$

where $f_{SSS}(N_{SSS})$ and $f_{NSSS}(N_{NSSS})$ are the cost-weight objective function

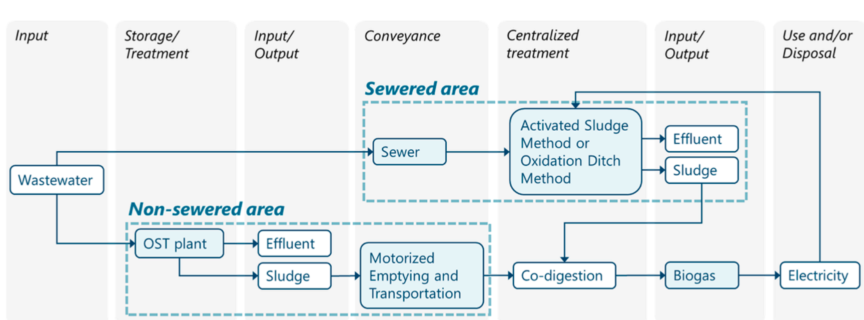

Fig. 1. The sanitation service chain analysed in this study.

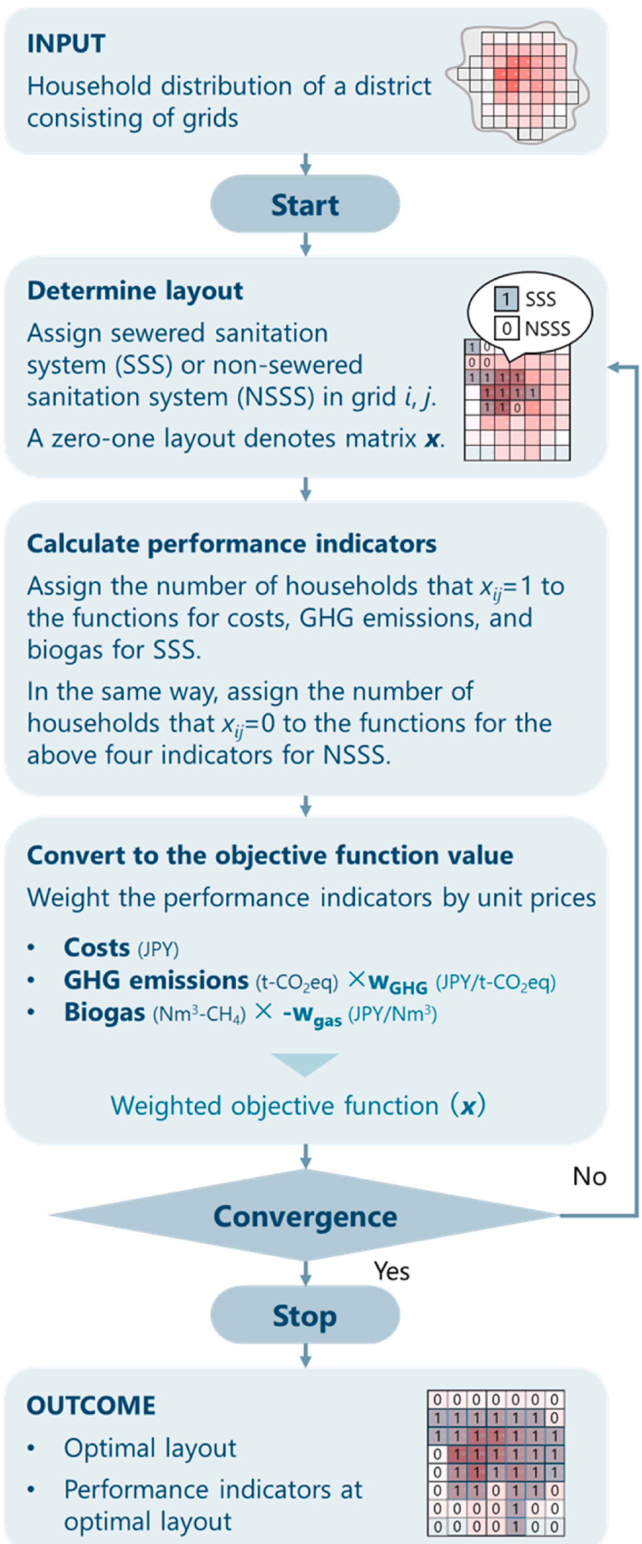

Fig. 2. The multi-objective optimization process using the Simulated Annealing method established in this study.

for sewered and non-sewered systems, respectively; $N_{SSS}$and N_{NSSS} are the number of households served by sewered and non-sewered systems in the first year, respectively; $C_{SSS_{capex}}$ and $C_{NSSS_{capex}}$ are 50-year Capex of sewered and non-sewered systems, respectively; $C_{SSS_{opex}}$ and $C_{NSSS_{opex}}$ are 50-year Opex of sewered and non-sewered systems, respectively; $GHG_{SSS_{cap}}$ and $GHG_{NSSS_{cap}}$ are 50-year GHG emissions from construction and installation of sewered and non-sewered systems, respectively; $GHG_{SSS_{ope}}$ and $GHG_{NSSS_{ope}}$ are 50-year GHG emissions from operation of sewered and non-sewered systems, respectively; V_{SSS} and V_{NSSS} are 50-year biogas volume from sludge from sewered and non-sewered systems, respectively; and, w_{GHG} and w_{biogas} are unit prices (Japanese yen: JPY) of GHGs and biogas, respectively. Derivations of these functions are provided in Supplementary Sections S2 to S6. In this study, the optimization problem is formulated to minimize the expected value of the objective function rather than its variability. Each facility within the sanitation system is assumed to follow an exogenously defined corrective (run-to-failure) maintenance policy. Within these modelling conditions, stochastic fluctuations in infrastructure deterioration processes or other external factors are not explicitly modelled, as incorporating such stochastic dynamics would not substantially alter the resulting optimal configuration.

The optimization seeks the ideal assignment of grid cells – defined by a binary decision variable $x_{i,j}$, where $x_{i,j} = 1$ if the grid is allocated to sewered system, and $x_{i,j} = 0$ if to non-sewered system. The set of $x_{i,j}$ is denoted as $\boldsymbol{x} = \{x_{i,j} | i = 1, \cdots, L/k; j = 1, \cdots, L/k\}$. An integrated objective function is defined by replacing N_{SSS} with $N_{SSS}(\boldsymbol{x}) = \sum_{i=1}^{L/k}\sum_{j=1}^{L/k} x_{i,j}N_{i,j}$ in Eq. (1) and N_{NSSS} with $N_{NSSS}(\boldsymbol{x}) = \sum_{i=1}^{L/k}\sum_{j=1}^{L/k}(1 - x_{i,j})N_{i,j}$ in Eq. (2), respectively:

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} f_{SSS}(N_{SSS}(\boldsymbol{x})) + f_{NSSS}(N_{NSSS}(\boldsymbol{x})), \tag{3}$$

$$\text{s. t.} \sum_{(p,q)\in\mathcal{N}_{i,j}} x_{p,q} > 0 \text{ if } x_{i,j} = 1 \ \forall x_{i,j}, \tag{4}$$

where $\mathcal{N}_{i,j} = \{(p,q) | |p - i| \le 1, |q - j| \le 1, (p,q) \ne (i,j)\}$ denotes the set of 8 neighboring cells around (i,j). At the grid boundaries, the summation over neighboring cells excludes those outside the index range $\{1, \cdots, L/k\}$. Eq. (4) indicates a constraint, which ensures connectivity among grids designated as sewered area. We employed the Simulated Annealing algorithm implemented in Python 3.12.4 to identify the global optimum. The optimization algorithm converged at its minimum objective function value after 9.5 million iterations.

2.3. Case study

To demonstrate the applicability of our model with real-world data, we conducted a case study in Ōsaki City, Miyagi Prefecture, Japan. The study area comprised a 16 km² residential zone in the city center,

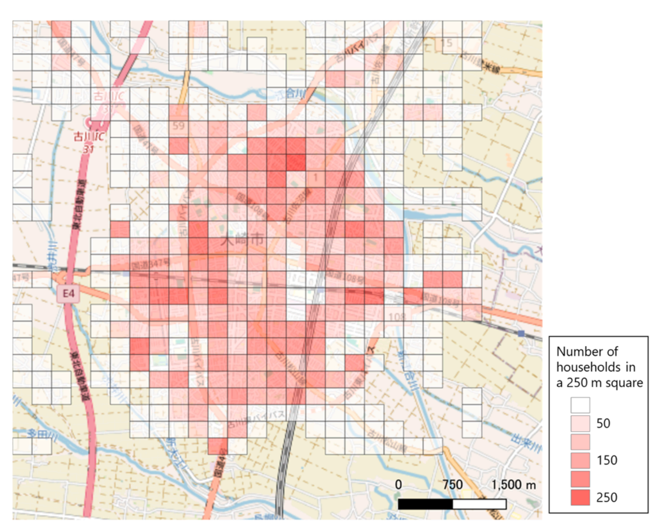

Fig. 3. Household distribution for the case study area in the beginning of the simulation period.

representing 2 % of the total area but approximately 40 % of the city's population (Fig. 3). This area was divided into 256 grids of a 0.25 km square each, with household counts ranging from 1 to 256 per grid, corresponding to 3 to 22,704 population equivalents. A uniform annual population decline of 0.5 % was assumed over a 50-year planning horizon based on the rate observed in 2023–2024 (IPSS, 2025). The unit price for greenhouse gases was set at JPY 5600 per t-CO_2eq, corresponding to the 2020 transaction price of renewable energy credits under Japanese emission trading system (Energy Information Center, 2025). The unit price for biogas was JPY 58 per Nm^3, based on reported energy recovery performance in which biogas-derived energy replaces electricity purchased at JPY 31 per kWh (Osaka City, 2019). Discount rate of 4 % for cost and 3 % for GHG emission calculations were applied.

2.4. Sensitivity analysis

The model's robustness was evaluated under the following scenarios. Given that household density is a key parameter in the objective function, the spatial distribution of residents has a significant influence on overall system performance. For instance, higher household density allows more households to connect to sewers, thereby reducing sewer maintenance costs. To evaluate the impact of household distribution on system performance, the model was applied to two additional hypothetical scenarios—a dispersed and a dense scenario—while maintaining the same average density of 3100 households per km^2 based on the 2020 census data. Both distributions were manually created from the 2020 census data. The maximum number of households within a 0.25 km squire grid was 211 in the 2020 census data, 200 in the dispersed scenario, and 270 in the dense scenario. The coefficients of variation, used as an index of spatial uniformity, were 73.1, 58.3, and 75.3 for the 2020 census data, dispersed, and dense scenarios, respectively.

In addition, system performance was evaluated under different population growth rate and labor costs. We assumed that the 2020 population remains unchanged over 50 years (hereafter denoted as the constant-population scenario). Labor costs differ across prefectures, fluctuate over time, and represent a major share of total expenditure. To capture this variability, labor costs 14 % above and 4 % below the baseline were tested based on the highest and lowest regional minimum wages (Ministry of Health Labour and Welfare, 2025). Labor costs were assumed to represent 14 %, 23 %, and 24 % of the total costs for WWTP

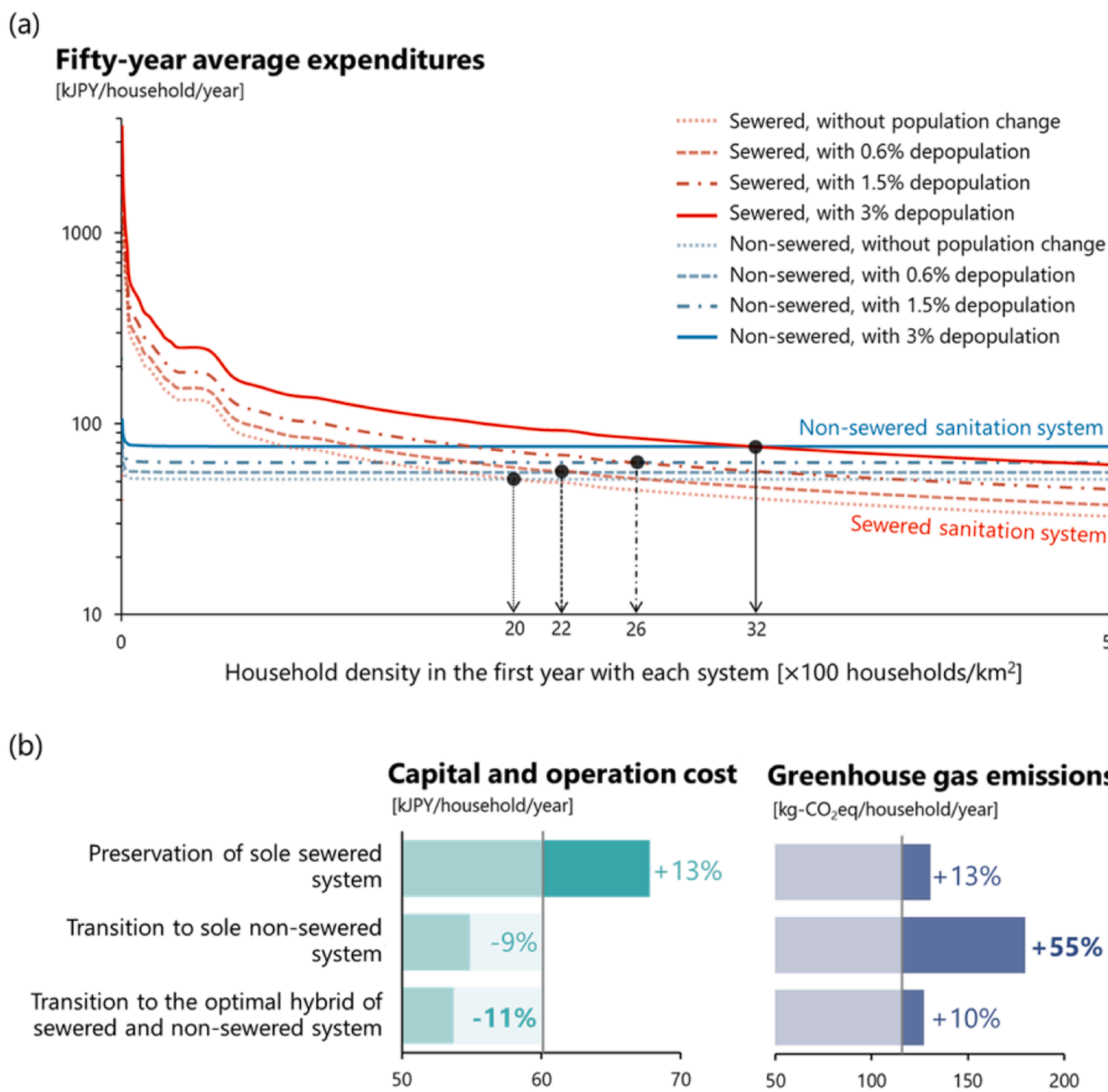

Fig. 4. (a) Impact of depopulation on the equilibrium of the fifty-year average expenditure between sewered and non-sewered systems. Solid and dots lines indicate the fifty-year average expenditures as a function of household density (blue for non-sewered system and red for sewered system) with annual depopulation by 0.6 %, 1.5 %, and 3 %. The intersections of blue line and red line are the cost-equilibrium household densities between sewered and non-sewered systems at each depopulation rate. (b) Total expenditures and GHG emissions in the three scenarios compared to the status quo (solid gray line), representing an optimistic scenario where the current system is maintained and the population served does not decline.

operation, sewer maintenance, and contraction, respectively (Japan Sewage Works Association, 2025; Ministry of Health Labour and Welfare, 2018).

3. Results and discussion

3.1. Impact of population decline on cost-effectiveness

Household density was used as a proxy for evaluating the cost-effectiveness of centralized sanitation systems, based on the principle that per capita costs decline with increased user numbers. Fig. 4a shows the impact of depopulation on the fifty-year average expenditure for scenarios either sole sewered system case or sole non-sewered system case, without considering their optimal integration. The relative cost-effectiveness of the sewered system compared to the non-sewered system is significantly influenced by household density. In sparsely populated areas, lower densities lead to higher per-household costs for both systems. In addition, the 50-year average household expenditure, obtained by dividing the total Capex and Opex by the number of served households, increases as the population decline. The cost parity point between sewered and non-sewered systems represents the minimum viable density for installing centralized sewerage. Without population decline, this threshold is approximately 2000 households per km^2; however, under a 0.6 % annual population decline (comparable to national trends in Japan), the break-even density increases to 2200 households per km^2. It increases further under rates exceeding 1.5 %, observed in roughly 10 % of prefectures or at smaller administrative levels. These findings suggest that preserving centralized sewer systems in areas below this density threshold may become economically unviable over the next 50 years if population decline continues.

Estimates under a 0.5 % depopulation scenario show that maintaining the sewered system would result in excessive economic and environmental burdens (Fig. 4b). Specifically, restoring an existing sewered system under population decline leads to a 13 % increase in household expenditures compared to the scenario where a new sewered system is implemented under stable population conditions. Transitioning to the non-sewered system mitigates the financial burden but significantly increases GHG emissions. This result clearly demonstrates the trade-off between economic and environmental impact.

3.2. Optimal hybridization of sewered and non-sewered systems

To address the limitations of the sole systems, we identified the optimal hybrid configuration of sewered and non-sewered systems for the case study area. This hybrid system—combining optimally located sewered and non-sewered systems—proves more advantageous, reducing capital and operational costs by 11 % while minimizing the increase in GHG emissions (Fig. 4b). The optimal spatial allocation of sewered and non-sewered systems is shown in Fig. 5a. Of the 22,704 total households, 15,661 (69 %) were assigned to sewered system, which were preferentially located in higher-density grid cells. The average household density was 2400 households per km^2 in sewered zones and 700 households per km^2 in non-sewered zones.

Fig. 5b compares the minimized objective function values for the optimal hybrid layout, a fully sewered layout, and a fully non-sewered layout. The breakdown of these values into performance indicators is shown in the stacked bar chart. Note that while the price-weighted biogas is stacked for visualization, it is subtracted in the weighted objective function, as described in Eqs. (1) and (2). The hybrid system outperforms both single-system scenarios in terms of cost and GHG emissions (Fig. 5c). Notably, capital expenditures constitute over 95 % of the costs of sewered system, with sewer rehabilitation alone contributing approximately 80 %, consistent with previous studies (Jung et al., 2018; Roefs et al., 2017) (Fig. S4b). In terms of GHG emissions, sewer rehabilitation contributes 58 % of sewered system-related emissions (Fig. S5b). On the other hand, non-sewered system produces 27 % higher GHG emissions, primarily due to the presence of anaerobic and aerobic treatment stages. The anaerobic stage offers advantages such as reduced electricity consumption for aeration and lower sludge volume compared to fully aerobic treatment, enabling long-term sludge storage in limited space. However, it also emits methane to the atmosphere. In addition, the subsequent aerobic stage requires blower-based aeration, consuming at least 35 W of power. By contrast, the oxidation ditch process in centralized treatment consumes roughly one-tenth of the electricity per capita, owing to economies of scale. The optimization process allocates centralized sewerage only to densely populated areas, thereby halving the required length of the piped network and simultaneously reducing the number of OST plants—major contributors to GHG emissions. As a result, the hybrid system minimized both costs and GHG emissions.

Regarding the amount of potentially recoverable biogas per unit cost, the hybrid system is comparable to the fully sewered case, suggesting its superior cost-effectiveness (Fig. 5c). However, the potential for biogas recovery is highest in the fully sewered scenario and declines as non-sewered adoption increases. This is because sanitary sewers collect wastewater with more undigested organic matter from toilets and kitchens. In contrast, sludge from OST plants is partially digested in the anaerobic stage at the source, resulting in reduced total biogas potential in the non-sewered system.

Mathematical optimization has been used as a valuable tool for identifying optimal levels of centralization and infrastructure layouts – including sewer networks, pumping stations, and WWTPs according to specific objectives (Pasciucco et al., 2022). It involves determining the optimal set of decision variables (i.e., controllable parameters) that minimize or maximize defined objective functions while satisfying system constraints. These objective functions typically represent key planning goals—such as minimizing capital and maintenance expenditures, reducing energy consumption, or maximizing resource recovery—and are formulated as functions of model variables related to infrastructure layout. This approach enables us to incorporate various factors and adapt to different urban contexts if the model functions in various geographical conditions. This study successfully applied mathematical optimization to identify the optimal degree of hybridization. The global optimum derived from this model provides a directly interpretable, spatially explicit layout of sewered and non-sewered systems. The model's output is intuitive and practical, making the framework particularly useful for informing system planning during the early stages of implementation.

Recent studies have successfully integrated spatial infrastructure layouts into multi-objective optimization frameworks, yielding Pareto-optimal solutions valuable for multi-criteria decision-making. Notable examples include the UrbanBEATS Planning-Support Tool, which selects decentralized stormwater solutions and optimizes spatial layouts (Bach et al., 2020); stormwater sewer network design models (Hesarkazzazi et al., 2022b, 2022a); design of the degree of (de)centralization of sewage collection conveyed to green-blue solutions (Bakhshipour et al., 2021); and the SUWStor model, which identifies optimal adjacency of pipelines and WWTPs capacity (Zhang et al., 2023). However, most previous studies have focused on stormwater or greywater systems and have not adequately addressed the treatment of domestic wastewater. Additionally, many optimization models demand high-resolution spatial datasets—including land use, population distribution, and topographic data—and significant computational resources, which may limit their applicability in data-scarce regions. In this study, we employed a canonical simulated annealing algorithm, which is known to be computationally demanding (about five hours on a standard laptop for the present case). Various enhanced versions of simulated annealing have been developed to accelerate convergence (e.g., Liang et al., 2014; Lu et al., 2021), and alternative metaheuristics have also been proposed (Rajwar et al., 2023). The optimization framework in this study was designed with these advanced algorithms in mind, allowing straightforward extension to larger-scale problems.

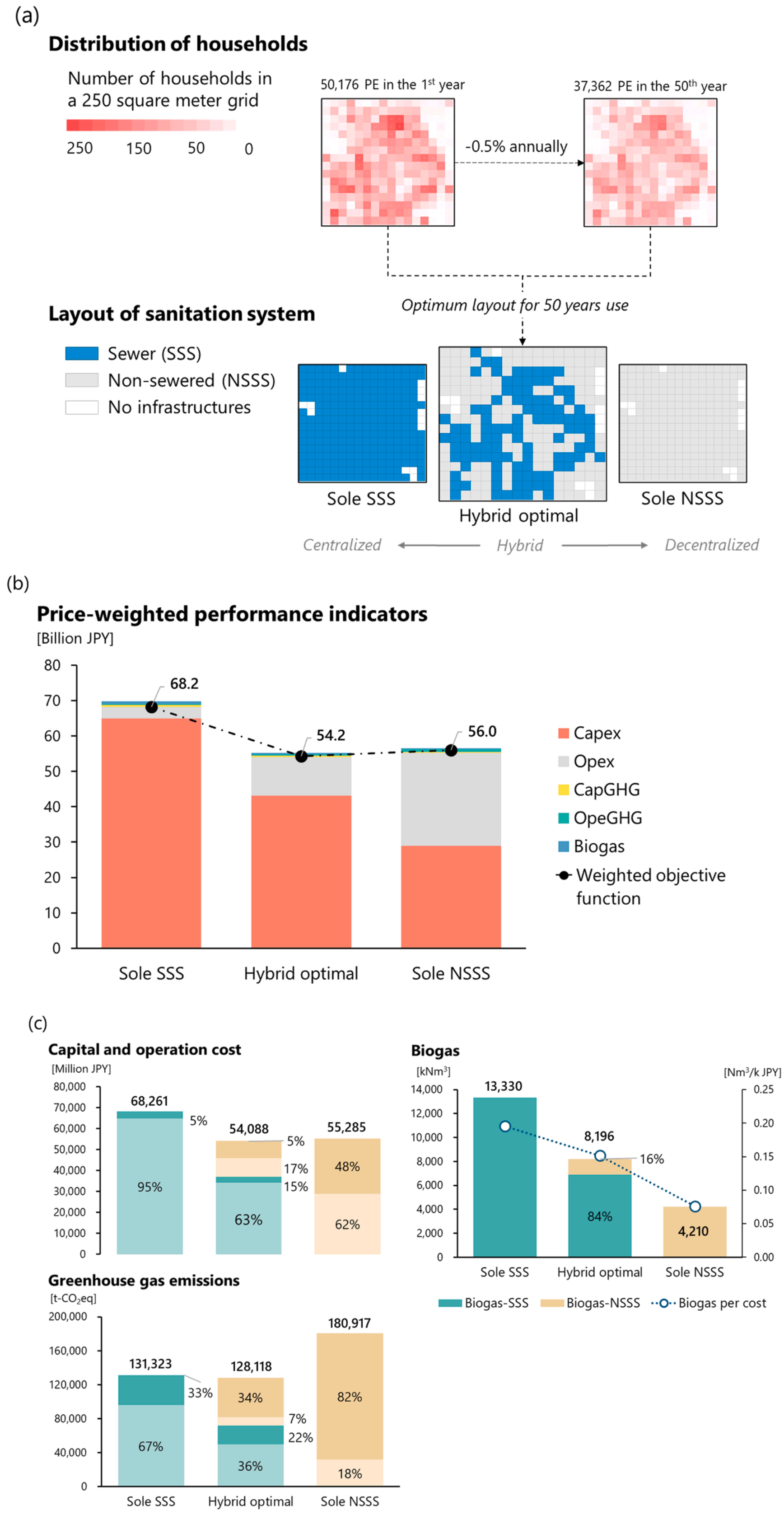

Fig. 5. (a) Optimal layout of sewered and non-sewered systems for a given household distribution and 0.5 % depopulation rate. (b) Comparison of price-weighted performance indicators at the optimal hybrid layout with those of the solely sewered (SSS) and solely non-sewered (NSSS) layouts. (c) Comparison of three performance indicators at the optimal hybrid layout with those of single-system (SSS and NSSS) cases.

A key strength of the framework is its ability to integrate multiple metrics through cost-based normalization, enabling multi-criteria evaluation. Nevertheless, the objective function is dominated by Capex and Opex due to their relatively high unit costs (Fig. 5b). The study assumes that under declining revenue conditions, economic efficiency is paramount. Testing alternative unit prices reflecting different policy contexts would add value to this framework. For instance, Sweden's carbon tax of SEK 1510 t-CO_2eq (Government Offices of Sweden, n.d.), which is approximately 4.4 times higher than the value used in this study at the exchange rate on November 11, 2025, does not alter the conclusion, as carbon pricing remains orders of magnitude lower than capital and operational expenditures (results not shown). When non-monetized aspects are prioritized (e.g., environmental goals), a better approach would be to adopt multi-objective algorithms that explore the Pareto frontier (Bakhshipour et al., 2021; Hesarkazzazi et al., 2022b). This approach would be needed if we were to make another model with a different non-sewered system that is more focused on resource recovery.

3.3. Sensitivity analysis

The dense scenario yielded the lowest objective function value, reflecting more efficient sewer connections within fewer grid cells (Fig. 6a and 6b). Although the overall impact is modest, this spatial concentration reduces long-term costs and GHG emissions by 0.8 %. Conversely, the dispersed scenario leads to a 13 % increase in GHG emissions compared to the sole sewered scenario due to greater reliance on non-sewered system (Fig. 6c). Similarly, biogas potential also declines by 11 % in the dispersed setting. In summary, the effectiveness of hybridizing sewered and non-sewered systems is modestly influenced by household distribution. As residential areas becomes more dispersed, total cost and GHG emissions approach those of the fully non-sewered scenario, although the biogas potential remains higher. In Japan, compact city policy has recently attracted much attention as a means to enhance urban sustainability (Ministry of Land Infrastructure Transport and Tourism, n.d.). The present findings provide useful insights for such initiatives, suggesting that low-density urban expansion is disadvantageous for both cost efficacy and environmental sustainability, particularly in sanitation planning.

In the constant-population and varied labor cost scenarios, the price-weighted performance indictor was minimized in the case of hybrid system, despite changes in the spatial allocation of sewered and non-sewer systems (Fig. 7 and Fig. S6). These results indicate that the hybrid approach outperforms both solely sewered and solely non-sewered systems across the tested parameter ranges. In the constant-population scenario, 93 additional households were allocated to sewered area. Compared with the baseline scenario, which is the conditions used in the case study, total cost and GHG emissions increased by 2.0 % and 4.9 %, respectively, owing to the larger populations and correspondingly higher operational cost and GHG emissions in both systems (Fig. 8). However, per-household cost and GHG emissions decreased by 9.5 % and 7.0 %, respectively, reflecting economies of scale.

In the scenario with a 14 % higher labor cost, 105 households from non-sewered areas were allocated to sewered areas, effectively mitigating the increase in operational labor costs, which accounts for about 30 % of total expenditures in non-sewered systems (Fig. S5a). In contrast, in the 4 % lower labor cost scenario, the number of households assigned to non-sewered systems increased substantially. Although the total cost remained lowest in the hybrid configuration due to the higher resource efficiency of non-sewered systems, the associated increase in OST plants led to slightly higher total GHG emissions than in the fully sewered case. Overall, these results demonstrate that the total GHG emissions are sensitive to the proportion of non-sewered households, which in turn depends strongly on the operational labor cost of non-sewered systems.

3.4. Technical solutions for further optimization

An analysis of GHG emission components in the non-sewered system (Fig. S5) revealed that OST-related direct and indirect emissions are the dominant sources. Methane and nitrous oxide emissions from biological processes account for 39 % of the total. Significant methane release occurs in the anaerobic stage used for wastewater storage and treatment in an OST plant. In addition, blower-related electricity use contributes 35 % of total emissions. Centralized treatment offers economies of scale in energy consumption, whereas non-sewered systems lack this advantage. Increasing the number of the OST plants introduces redundancy in treatment components, resulting in higher total electricity consumption than in sewered systems. Consequently, increasing non-sewered adoption significantly increases total GHG emissions. Achieving parity with sewered-system emissions would require a 33 % reduction in onsite operational emissions, which is achievable through intermittent aeration (Ma et al., 2020; Zeng et al., 2018). Other potential measures include short-term sludge storage (with increased transport needs), onsite aerobic processes such as vermicomposting, and source-separated urine collection to mitigate nitrous oxide emissions.

The optimization model in this study is designed for a scenario involving sludge consolidation at a centralized treatment plant and the offsite reuse of biogas. The amount of biogas decreases as non-sewered adoption increases, due to the lower methane conversion ratio of *Johkasou* sludge (r_{gas} in Table S1), which is likely a result of the initial anaerobic stage in the *Johkasou* system. Our analysis demonstrates that fuel and GHG costs for sludge transport are minimal compared to other expenses (Figs. S4a and S5a), although labor costs for collection account for 30 % of total expenditures. These results support the need for implementation of optimized sludge collection systems with more frequent, efficient scheduling.

3.5. Limitations and outlook

Conventional centralized wastewater infrastructure represents a significant capital investment; however, population decline and aging demographics are increasingly misaligned with such systems' capacity. To identify more viable sanitation strategies for shrinking cities, this study evaluated population decline across infrastructure life cycles and proposed a hybrid sewered and fully road-transported, non-sewered sanitation system optimization model. Downsizing existing fully sewered system into the hybrid system was shown to be both economically and environmentally advantageous. The proposed framework thus offers a promising approach to rightsizing infrastructure for smaller urban populations through integrated asset planning. Narayan et al. advocate for a portfolio approach to sanitation planning, which strategically combines multiple system types to meet diverse service needs and sustainability goals (Narayan et al., 2024). While such coexisting systems have been explored in the context of rapidly urbanizing regions ("Co-existing sanitation systems in dense urban areas," 2024), this study demonstrates that they are equally, if not more, applicable in shrinking societies. Although the optimization model was developed for population-decline scenarios, it could be adapted for population growth, for example in low- and middle-income countries, where infrastructure preservation is a significant challenge due to financial, institutional, and technical constraints (United Nations, 2021). These diverse contexts can be accommodated by modifying the current model, including omitting the infrastructure disposal components, replacing the spiral-wound lining method with open-cut construction, and updating the model parameters such as population growth rate.

Nevertheless, there are important drawbacks with the current version of the model. In the proposed model, each facility in the sanitation system is assumed to have a deterministically assigned service life. This setting is consistent with the study's objective of minimizing the expected value of the objective function under an exogenously defined corrective maintenance policy, and such a policy is commonly

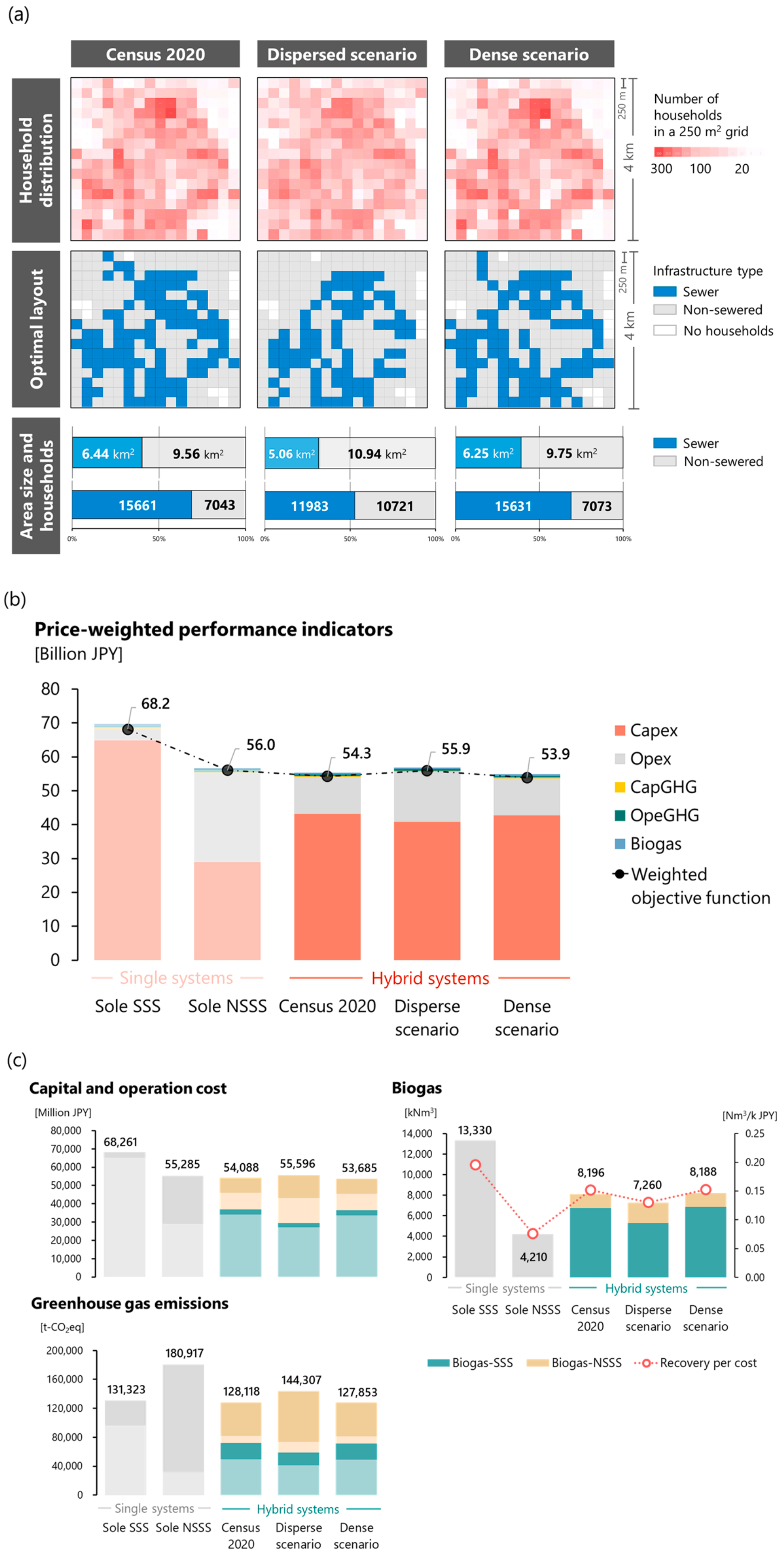

Fig. 6. (a) Optimal layouts of sewer and non-sewered system for the following different distribution pattens; national census in 2020, a hypothetical scenario that households are randomly dispersed, and another hypothetical scenario that households are more clustered. All scenarios have 22,704 households in 16 km^2 (equivalent to 230 households/km^2). (b) Comparison of price-weighted performance indicators at the optimum layouts of hybrid systems and sole system cases. (c) Comparison of three performance indicators at the optimum layouts of hybrid systems.

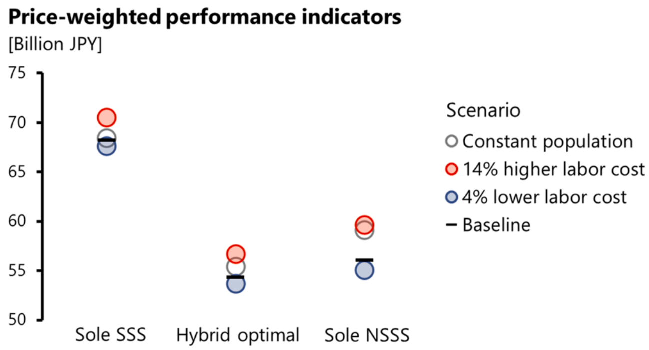

Fig. 7. Price-weighted performance indicators at the optimum layouts of hybrid systems, compared to that in sole sewered and sole non-sewered system case.

adopted in infrastructure management in practice. However, under these modelling conditions, it is not possible to evaluate or optimize asset-management or operational strategies that respond to uncertain deterioration of facilities during the planning period. Although this study did not address this issue due to the extremely high dimensionality of the decision variables in the resulting mathematical optimization problem, an important direction for future work will be to extend the framework by incorporating stochastic deterioration models (Mizutani and Yuan, 2023) and deriving condition-based optimal intervention policies within a stochastic control framework (Mizutani et al., 2020). Such an extension would enable the simultaneous optimization of both the initial planning at the beginning of the period and the management strategies during the planning horizon.

Both the sewered and non-sewered technologies analysed in this study lack sufficient functions for nutrient removal and recovery. Centralized wastewater treatment systems combine various wastewater streams and depend on fully piped conveyance networks, which constrain opportunities for water and nutrient recycling while increasing pollution discharges to receiving water bodies (van Puijenbroek et al., 2019). Although advanced biological processes (e.g., nitrification–denitrification, enhanced biological phosphorus removal) can improve nutrient removal, they are technically complex and energy-intensive. The *Johkasou* system includes nitrification and denitrification processes for ammonium removal; however, it does not address phosphorus removal. As a result, its effluent may contribute to eutrophication in the downstream water bodies and limits its applicability in a circular society, where wastewater treatment systems are designed to support nutrient and water recycling. To fully leverage the benefits of the proposed optimization framework, future research should incorporate a broader range of resource-oriented sanitation technologies and tailor the model to maximize water and nutrient recovery in addition to minimizing cost and GHG emissions.

When appropriate technologies are incorporated, non-sewered systems can increase opportunities for local reuse of wastewater resources (Larsen et al., 2016). For example, separating wastewater flows at the point of generation facilitates, such as through urine, blackwater and/or greywater separation, increases the potential for resource recovery. This enables not only water reuse, but also energy recovery from hot water and biogas generation from feces, and nutrients recovery, particularly from urine. Source-separation sanitation systems have been implemented at various spatial scales, including individual households. Garrido-Baserba et al. propose source separation at the scale of neighborhood blocks, coupled with onsite reuse of recovered resources (e.g., anaerobic co-digestion, vertical farming, and rainwater harvesting) as well as photovoltaic energy generation (Garrido-Baserba et al., 2024). Indirect potable water reuses, such as the so-called NEWater in Singapore, has been successfully implemented as a district-level system (Lefebvre, 2018). Another recent district-level system is the "Three Pipes Out" systems in the new Oceanhamnen district of Helsingborg, Sweden. The potential for resource recovery can increase with larger service populations and broader spatial coverage. However, such systems often require multiple pipe networks for different streams or road-based transport systems, unlike conventional centralized systems that rely on

	Dispersed households' distribution	Dense households' distribution	Constant population	14% higher labor cost	4% lower labor cost
Number of households in sewered area	-3,678	-30	+93	+105	-1,120
50-year total cost	+2.8%	-0.7%	+2.0%	+4.3%	-1.3%
Capex for SSS	-20.5%	-1.4%	+0.8%	+4.1%	-8.5%
Capex for NSSS	+52.0%	+0.4%	+1.2%	+1.6%	+14.8%
Opex for SSS	-15.6%	-0.3%	+4.6%	+2.6%	-5.5%
Opex for NSSS	+52.2%	+0.4%	+7.1%	+8.3%	+12.6%
50-year average household cost	+2.8%	-0.7%	-9.5%	+4.3%	-1.3%
50-year total GHG emissions	+10.9%	-0.2%	+4.9%	-0.3%	+3.5%
CapGHG for SSS	-17.4%	-0.9%	+1.0%	+0.6%	-6.2%
CapGHG for NSSS	+52.2%	+0.4%	+1.2%	-1.5%	+15.9%
OpeGHG for SSS	-20.0%	-0.2%	+8.4%	+0.6%	-6.0%
OpeGHG for NSSS	+52.2%	+0.4%	+8.0%	-1.5%	+15.9%
50-year average household emissions	+10.9%	-0.2%	-7.0%	-0.3%	+3.5%
50-year total biogas	-10.1%	-0.1%	+12.8%	+0.0%	-3.8%
Biogas from SSS	-21.9%	+1.9%	+12.8%	+0.1%	-7.7%
Biogas from NSSS	+45.7%	-3.9%	+12.8%	-0.2%	+17.5%

Fig. 8. Change in the number of households in sewered area and performances in five scenarios (dispersed and dense households' distributions, constant population, 14 % higher and 4 % lower labor cost), compared to the baseline scenario.

a single-pipe configuration. This complexity introduces potential trade-offs between the maintenance and energy costs of (small-) network infrastructure and the quantity of recoverable resource.

One recommendation would be to extend the scope of the optimization framework presented here to support the selection of appropriate resource-recovery technologies and their corresponding spatial scales. The generic structure of the existing model can be adapted to various sanitation technologies if the generalized performance indicators are defined for each resource-oriented sanitation technology. In scenarios involving intensive resource recovery, it is valuable to incorporate a metric for human health as a constraint in the optimization model, since some treatments are not sufficient on their own to remove pathogens and require non-technical barriers or post-treatment measures, such as a long-term storage (Oishi et al., 2023). We emphasize that our framework facilitates the implementation of a variety of sanitation infrastructure concepts, including those with water and nutrient recovery, if the specific problems are accurately identified and the optimization models, including objective functions and constraints, are appropriately formulated.

4. Conclusions

This study demonstrates that population decline undermines the cost-efficiency of maintaining conventional sewered systems over long time horizons. Under a scenario of 0.5 % annual depopulation, maintaining the existing sewered system increases the average 50-year per-household expenditure by 13 % compared to a scenario without population decline. Meanwhile, transitioning to a fully non-sewered system reduces the financial burden but results in a 55 % increase in GHG emissions. A promising strategy is to incorporate non-sewered systems into existing sewered infrastructure, forming a hybrid configuration tailored to spatial population dynamics. Using a newly developed multi-objective optimization framework, we identified the optimal layout of sewered and non-sewered systems that minimizes long-term expenditures and GHG emissions. The case study confirmed that hybrid systems outperform single-technology solutions in both economic and environmental terms. Optimal integration of sewered and non-sewered systems reduces capital and operational costs by 11 % while limiting GHG emissions growth. Additional benefits are achieved through optimized onsite treatment technologies that reduce operational GHG emissions by 33 %, and through efficient sludge collection or onsite resource reuse. Furthermore, the model's generalized formulation and cost-based normalization enable its application to diverse settings with varying policy priorities. The proposed framework can be tailored to include a wider range of resource-oriented sanitation technologies that enable nutrient and water recovery through source separation. Incorporating such technologies and tailoring system configurations to local conditions can enhance the framework's applicability for planning circular and decentralized sanitation systems with improved environmental and resource recovery performance.

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CRediT authorship contribution statement

Wakana Oishi: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daijiro Mizutani:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition. **Yuto Nakazato:** Software, Data curation. **Jennifer McConville:** Writing – review & editing. **Daisuke Sano:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.125135.

Data availability

Data will be made available on request.

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