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Operating a wastewater system at full capacity? Evaluating options from centralized to decentralized using spatial multicriteria analysis

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ABSTRACT

Urban development pressures, aging infrastructure, and growing environmental constraints are forcing many municipalities to reconsider conventional wastewater management strategies. In Quebec, Canada, as in many regions, centralized systems are approaching capacity limits, while decentralized and hybrid configurations remain underused, despite their potential to provide more context-sensitive solutions. Previous multi-criteria decision-analysis (MCDA) studies have either focused on non-spatial technology selection or applied spatial MCDA mainly to green stormwater management infrastructure, leaving a gap for a spatially explicit, participatory comparison of wastewater system configurations across scales.

This study develops a spatial MCDA decision-support framework based on value-focused thinking that integrates stakeholder-defined objectives into a planning support system to compare centralized, decentralized, and hybrid wastewater systems. The approach is structured around two system-specific objective hierarchies that jointly represent implementation opportunities and territorial needs and operationalizes these objectives using spatial indicators and value functions.

Applied to a medium-sized municipality in southern Quebec, the results show that suitability patterns are strongly determined by urban form, environmental vulnerability, and infrastructure constraints, and that no single system type is optimal across the territory. Hybrid configurations, particularly those combining infiltration and surface discharge, consistently achieve the highest suitability across both opportunity- and need-based perspectives, whereas purely centralized solutions show limited alignment with spatially distributed needs. One-at-a-time extreme-weight sensitivity analysis further demonstrates the influence of stakeholder preferences on spatial prioritization, highlighting the framework's contribution to transparency. Although case-specific, the proposed participatory spatial MCDA approach provides a transferable decision-support framework for strategic wastewater planning in municipalities facing similar capacity and sustainability challenges.

1. Introduction

A wastewater system refers to the infrastructure and processes used to collect, treat, and manage wastewater, and to discharge or reuse treated effluent in compliance with public health and environmental standards (USEPA 2004; ISO 2019). Wastewater systems span a continuum from fully centralized to decentralized configurations, including hybrid approaches that combine multiple scales. Centralized systems—characterized by extensive sewer networks and large-scale treatment facilities—have historically dominated in industrialized

contexts due to their efficiency and economies of scale (Bichai and Flamini, 2018; De Gisi et al., 2018; Eggimann et al., 2015; Jung et al., 2018; Maurer et al., 2013). However, they present limitations related to high capital and energy costs, and constrained opportunities for resource recovery (Kalbar and Lokhande, 2023; Pasciucco et al., 2022; Saadatinavaz et al., 2024). Decentralized systems operate closer to wastewater sources and treat smaller volumes, offering greater flexibility, reduced conveyance needs, and adaptability to low-density or rapidly developing areas (Pasciucco et al., 2022; Eggimann et al., 2016; Eggimann et al., 2016; Lüthi et al., 2016; Oakley et al., 2010). Their

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implementation, however, remains context-dependent and influenced by local institutional, environmental, and regulatory conditions. Hybrid systems provide an intermediate strategy that integrates centralized and decentralized components, enabling localized treatment combined with shared infrastructure and operational coordination (Beutler et al., 2024; Tchobanoglous, 2019). More broadly, previous wastewater studies have shown that combining complementary treatment or operational approaches can improve system robustness and performance under complex treatment conditions (Danaee et al., 2025). These configurations can reduce infrastructure costs and alleviate pressure on centralized systems, particularly in peri-urban contexts (Beutler et al., 2024; Tchobanoglous, 2019). Additional details on wastewater system configurations and their characteristics are provided in Text SI-1 (Supplementary materials).

Selecting wastewater systems requires addressing multiple, often competing objectives, including environmental performance, cost, operational reliability, land availability, and regulatory compliance (Beutler et al., 2024; Hoffmann et al., 2020; Solomon et al., 2025; Spiller et al., 2015; Zheng et al., 2016). Previous studies have demonstrated that wastewater treatment technologies can exhibit substantially different removal performances and operational constraints depending on process configuration and target contaminants, further highlighting the complexity of wastewater system selection (Asgharian et al., 2017). These decisions are further shaped by stakeholder priorities and spatial constraints, leading to context-specific solutions rather than universal optima (French and Geldermann, 2005; Ko et al., 2024; Makropoulos et al., 2007). This complexity highlights the need for structured decision-support approaches capable of integrating diverse criteria, stakeholder preferences, and spatial variability (Pasciucco et al., 2022; Ko et al., 2024).

A variety of decision-support instruments are employed for this purpose, including multi-criteria decision analysis (MCDA) (Renfrew et al., 2024; Juznić-Zonta et al., 2022), optimization algorithms and mathematical programming techniques (Antunes et al., 2002), life-cycle assessment (LCA) (Safarpour et al., 2022), and modular and adaptive approaches (Chamberlain et al., 2014). While supporting systematic evaluation of wastewater alternatives, each has limitations. Optimization and mathematical programming models typically privilege cost minimization and infrastructure efficiency but less effectively incorporate multi-dimensional criteria and heterogeneous stakeholder priorities (Antunes et al., 2002). Recent studies have expanded these approaches through machine-learning and hybrid optimization techniques, including the coupling of surrogate models with metaheuristic algorithms to improve predictive and optimization capabilities in complex engineering applications (Taghavi Khangah et al., 2024). However, their mathematical formulation also tends to be complex—featuring non-linear objectives, discrete variables, and non-linear constraints—requiring sophisticated algorithms and computational techniques to obtain feasible solutions. LCA offers robust means of quantifying environmental burdens and comparing sustainability outcomes across technologies and scales, but it does not capture regulatory, social, or qualitative preferences, which typically require complementary participatory or multi-criteria processes (Safarpour et al., 2022). Modular and adaptive approaches provide flexibility and facilitate the exploration of alternative system configurations, yet they often emphasize technical diagnostics and operational adaptability rather than explicit trade-offs among environmental, economic, and social objectives; additional decision layers are therefore needed to structure multi-objective comparison (Chamberlain et al., 2014).

Taken together, these constraints indicate that no single analytical approach captures the full spectrum of considerations involved in wastewater system selection. In practice, wastewater planning requires balancing economic, environmental, technical, spatial, regulatory, and social dimensions simultaneously, while also accounting for stakeholder priorities and local context (Ko et al., 2024; Ko, 2025). This need for integrated evaluation has led to growing interest in MCDA, which is

particularly well suited to situations involving competing objectives and heterogeneous decision criteria. Unlike optimization or single-objective assessment approaches, MCDA explicitly structures trade-offs among multiple dimensions and enables the incorporation of both quantitative and qualitative information into the decision-making process. The MCDA framework also facilitates stakeholder participation by making preferences and evaluation criteria transparent, thereby improving the legitimacy and interpretability of planning outcomes (Beutler et al., 2024; Lienert et al., 2015). For these reasons, MCDA has increasingly been applied in wastewater and urban water management to support strategic infrastructure planning under complex and uncertain conditions.

MCDA is particularly useful for evaluating wastewater management strategies by integrating economic, environmental, and social criteria with stakeholder preferences (Zheng et al., 2016; Ko et al., 2024; Lee et al., 2013; Soleimani, 2023). It is widely regarded as an umbrella term for formal approaches that explicitly account for multiple criteria when supporting individuals or groups in exploring consequential decisions (Belton and Stewart, 2002). Common MCDA methods include Multi-Attribute Value Theory (MAVT), the Analytic Hierarchy Process (AHP), TOPSIS, fuzzy logic approaches, and outranking methods such as ELECTRE and PROMETHEE, and entropy-based weighting techniques, each addressing trade-offs differently (Ko et al., 2024; Keeney and Raiffa, 1993; Saaty, 1980; Sharma et al., 2023; Figueira et al., 2013; Figueira et al., 2005; Jamali and Abbasalizadeh, 2021). Among these, Value-Focused thinking (VFT) emphasizes defining fundamental values and objectives prior to generating alternatives, supporting strategic and sustainability-oriented planning (Lacroix et al., 2024; Keeney, 1996).

However, conventional MCDA often underrepresents spatial constraints critical to wastewater planning. Integrating MCDA with Geographic Information Systems (GIS) enables explicit consideration of proximity, connectivity, and land-use, improving spatial relevance and operational realism of decisions (Malczewski and Rinner, 2015; Kuller et al., 2019). Yet important gaps remain in MCDA applications to infrastructure planning. Criteria selection and weighting are often insufficiently standardized or participatory, introducing potential biases, while inconsistent method and vague indicators reduce transparency (Renfrew et al., 2024). Moreover, comprehensive benchmarking across centralized, decentralized, and hybrid systems is still limited, and trade-offs among these configurations are rarely addressed. Previous studies have often evaluated these configurations separately because they differ substantially in spatial scale, infrastructure architecture, operational requirements, governance structures, and performance indicators, complicating direct comparison within a unified analytical framework (Eggimann et al., 2015; Xue et al., 2015; Sapkota et al., 2016; Poustie et al., 2015). In many cases, centralized systems have been assessed using network- and treatment-oriented performance metrics, whereas decentralized approaches have been evaluated through localized sustainability or resource-recovery perspectives, resulting in fragmented assessment methodologies (Sha et al., 2024; Bouziotas et al., 2019; Sartorius et al., 2018). Hybrid systems further increase methodological complexity because they combine centralized and decentralized components operating across multiple spatial and administrative scales. Consequently, trade-offs among these configurations are rarely addressed within a consistent GIS-MCDA framework (Poustie et al., 2015). In addition, regulatory constraints and stakeholder dynamics are often overlooked, limiting the applicability of existing approaches to real-world transition planning (Duque et al., 2024).

To address these gaps, this study builds on the Spatial Suitability Analysis Tool (SSANTO), a GIS-MCDA-based planning support system originally developed for blue-green infrastructure (BGI) planning in Melbourne (Kuller et al., 2019; Kuller et al., 2017) and recently adapted to Quebec municipalities (Lacroix et al., 2024). SSANTO evaluates spatial suitability for two complementary perspectives: territorial opportunities and needs. SSANTO was selected as the foundation for this

study because it combines several methodological characteristics particularly relevant to wastewater infrastructure planning. First, the framework integrates VFT with GIS-based MCDA, enabling explicit linkage between stakeholder values, hierarchical objective structuring, and spatial suitability analysis (Lacroix et al., 2024; Kuller et al., 2019). Second, SSANTO emphasizes transparency and transferability through the use of standardized value function, participatory weighting procedures, and modular workflow design, thereby facilitating adaptation across planning contexts and infrastructure systems (Lacroix et al., 2024). Although the framework was developed and applied within the Quebec context, its modular GIS-MCDA structure is intended to support transferability to other jurisdictions. Nevertheless, transferring the framework internationally would require adaptation of regulatory constraints, environmental thresholds, infrastructure standards, and spatial indicators to reflect local governance structures, climatic conditions, and wastewater management practices. Unlike many spatial planning systems that primarily focus on technical suitability mapping or predefined indicator aggregation, SSANTO explicitly supports structured trade-off analysis among competing environmental, social, economic, and spatial objectives. These characteristics make the framework particularly suitable for evaluating centralized, decentralized, and hybrid wastewater management strategies under context-specific conditions. Building on this framework, we develop a GIS-MCDA decision-support approach for wastewater systems planning that supports spatially explicit comparison of centralized, decentralized, and hybrid systems. The approach is applied to a case study city in southern Quebec, Canada, representative of northern-climate municipalities facing demographic growth and infrastructure constraints.

This study addresses the following research question: To what extent can a GIS-based, value-focused MCDA framework improve the transparency, consistency, and spatial relevance of trade-off analysis among centralized, decentralized, and hybrid wastewater management strategies? To address this question, this study aims to: (1) develop a hierarchical, value-focused objective structure for wastewater system selection; (2) refine and validate this structure through stakeholder participation; (3) translate objectives into spatially explicit indicators

and standardized value functions; and (4) implement the framework into a GIS-MCDA planning support system and test its application to a case study city.

By integrating value-focused thinking with spatial MCDA, this research contributes a structured, transparent, and transferable decision-support approach for wastewater system planning, enabling context-sensitive and evidence-based comparison of alternative system configurations across scales. The proposed approach can support stakeholders in exploring non-conventional options, providing an opportunity to move away from long-term infrastructural and institutional lock-in when making decisions on system investments that will impact urban sustainability over decades.

2. Material and methods

2.1. Conceptual framework

This study develops a GIS-MCDA framework grounded in VFT (Keeney and Raiffa, 1993; Keeney, 1996) and rational decision-making principles (Eisenführ et al., 2010). The framework integrates stakeholder values, expert knowledge, scientific evidence, and spatial analysis for wastewater planning. System boundaries were defined from regulations and refined through stakeholder input. Engagement relied on workshops aligned with the GIS-MCDA process, enabling iterative feedback and validation. The methodology follows a structured workflow (Fig. 1) inspired from a previous application of SSANTO to BGI planning, described in details in (Lacroix et al., 2024), from the elicitation of spatially-relevant criteria formulated as objectives (Steps 1–2), followed by their organization into system-specific hierarchies and stakeholder validation (Steps 3–5). The framework subsequently integrates geospatial datasets (Step 6), expert-derived value functions that translate spatial data into suitability scores, and stakeholder preferences expressed as objectives' weights (Steps 7–8), which are combined within a spatial suitability analysis and a one-at-a-time (OAT) extreme-weight sensitivity analysis (Steps 9–10). Each step is detailed in the subsequent subsections.

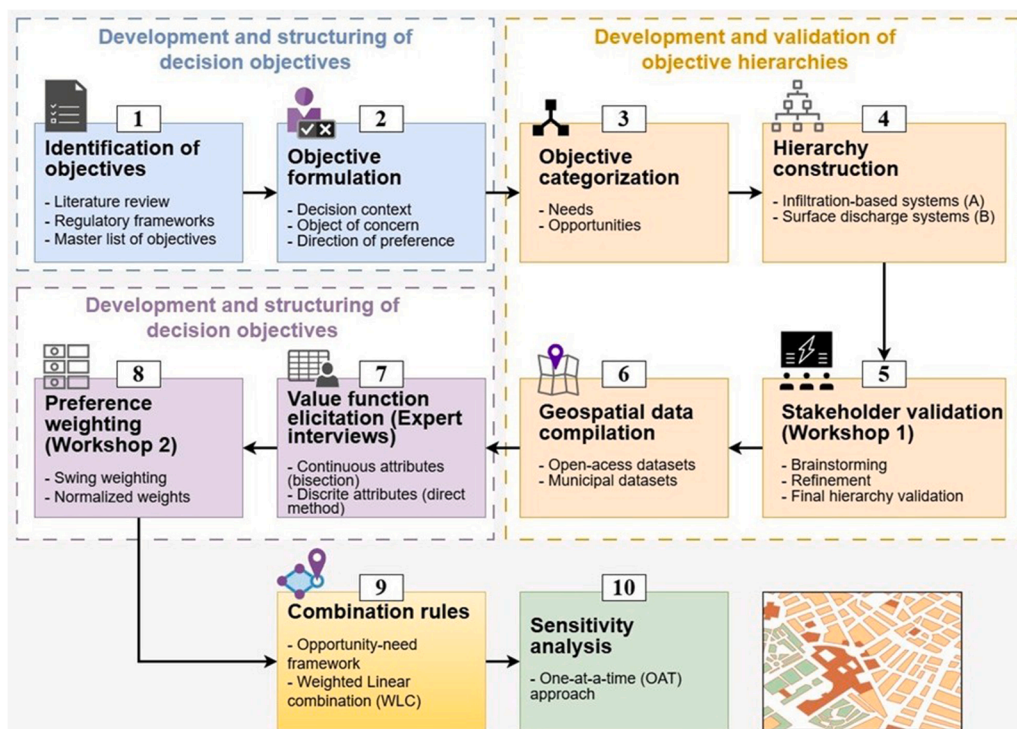


Fig. 1. GIS-MCDA workflow based on VFT for wastewater system planning.

2.2. Regional context for the case study

The study examines a medium-sized municipality within southern Quebec (Canada), with approx. 570,000 residents across 1000 km² of mixed urban and agricultural land (COBAMIL 2013). Ongoing urban growth, including high-density Transit-Oriented Development (60 households/ha) and lower-density redevelopment zones (21 households/ha) (Communauté métropolitaine de Montréal 2025), has prompted reassessment of centralized, decentralized, and hybrid wastewater strategies.

The municipality lies within a watershed crossed by two tributaries and shares receiving waters with 14 wastewater treatment facilities (WWTFs - Fig. 2). Its mechanized biofiltration WWTF discharges into this system, contributing to nutrient loads and fecal contamination (COBAMIL 2013). Clay-rich Champlain Sea deposits limit groundwater recharge and complicate construction, while agricultural areas increase groundwater contamination risks (COBAMIL 2013).

2.3. Development and structuring of decision objectives

A master list of objectives was developed to support systematic elicitation and reduce omission bias. The list was compiled through a targeted review of academic and grey literature on wastewater decision-making, focusing on criteria used in previous MCDA applications, complemented by Quebec and other North American regulatory guidelines (Ministry of Environment of Quebec 2015; USEPA 2012). Previous studies indicate that spatial decision-making frameworks primarily emphasize technical and physical constraints (e.g., topography, land use, hydrology, infrastructure proximity), while environmental, social, and governance dimensions are often underrepresented (Hamlat et al., 2013; Awawdeh et al., 2023). To address this, the set of objectives

was designed to integrate technical feasibility with environmental protection, public health, and social considerations. Further details on objectives development and structuring are provided in Text SI-2.

Objectives were formulated following standard decision-analysis principles, including: (i) a clear definition of the decision context (selection of wastewater management systems), (ii) explicit identification of the object of concern, and (iii) specification of the preferred direction (e.g., maximize/minimize). All objectives were expressed measurably to ensure consistency and preferential independence among criteria (Eisenführ et al., 2010).

Sixteen objectives were structured into two complementary perspectives: (i) Opportunities, representing areas where systems can be effectively implemented; (ii) Needs, representing areas where intervention is most required. Additionally, two system-specific hierarchies were defined to distinguish: (i) Onsite wastewater treatment with infiltration (OWTF), focusing on infiltration capacity, groundwater protection, and site suitability; (ii) Surface water discharge systems (SDS), emphasizing infrastructure feasibility, cost efficiency, and conflict minimization.

Each objective was associated with a measurable spatial attribute to enable GIS-MCDA integration. A conceptual synthesis of the main drivers and constraints considered for both systems is presented in Fig. 3, while the complete list of objectives, attributes, and literature sources is provided in Tables SI-1 to SI-3.

2.3.1. Development and validation of the hierarchies of objectives: needs and opportunities

To support prioritization and maintain a clear decision structure, objectives were grouped into two suitability perspectives that underlie the SSANTO framework for BGI planning: opportunities and needs (Lacroix et al., 2024; Kuller et al., 2019). The *opportunities* perspective

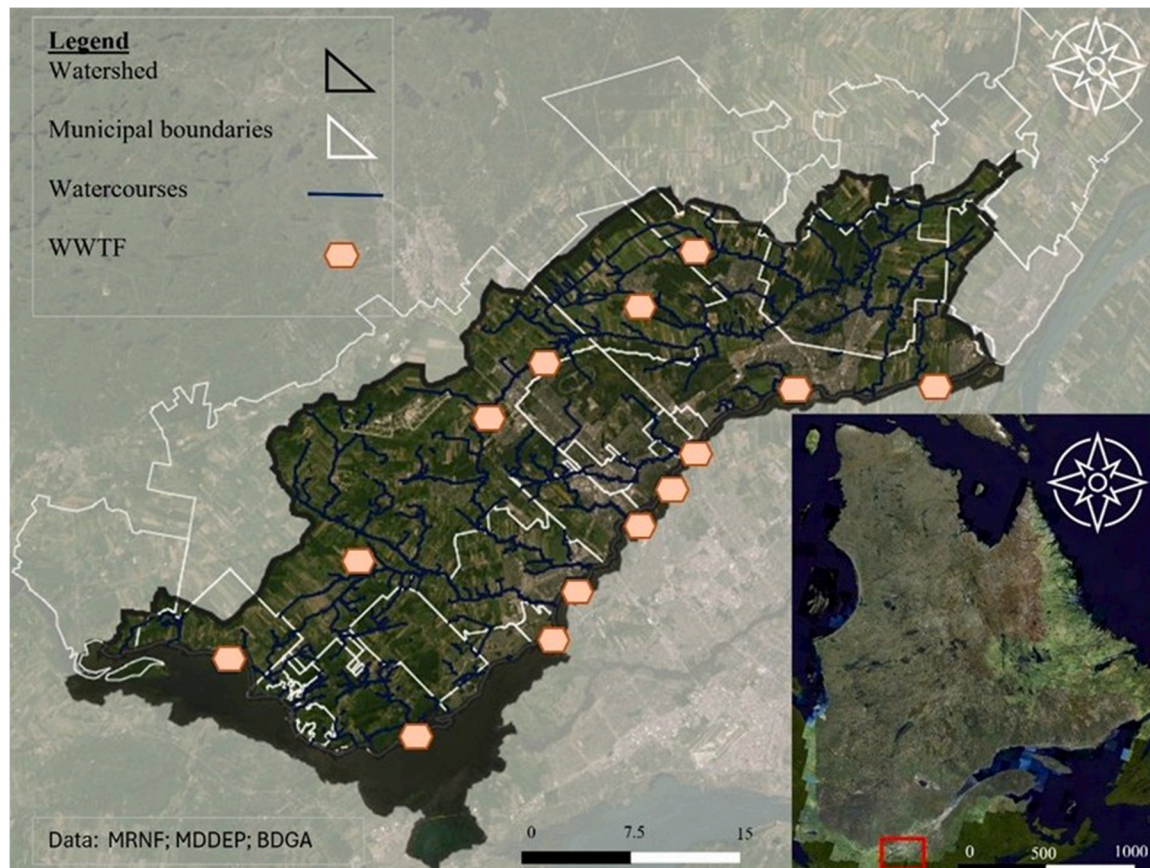


Fig. 2. Geographic location of the study area, including wastewater treatment facilities (WWTFs).

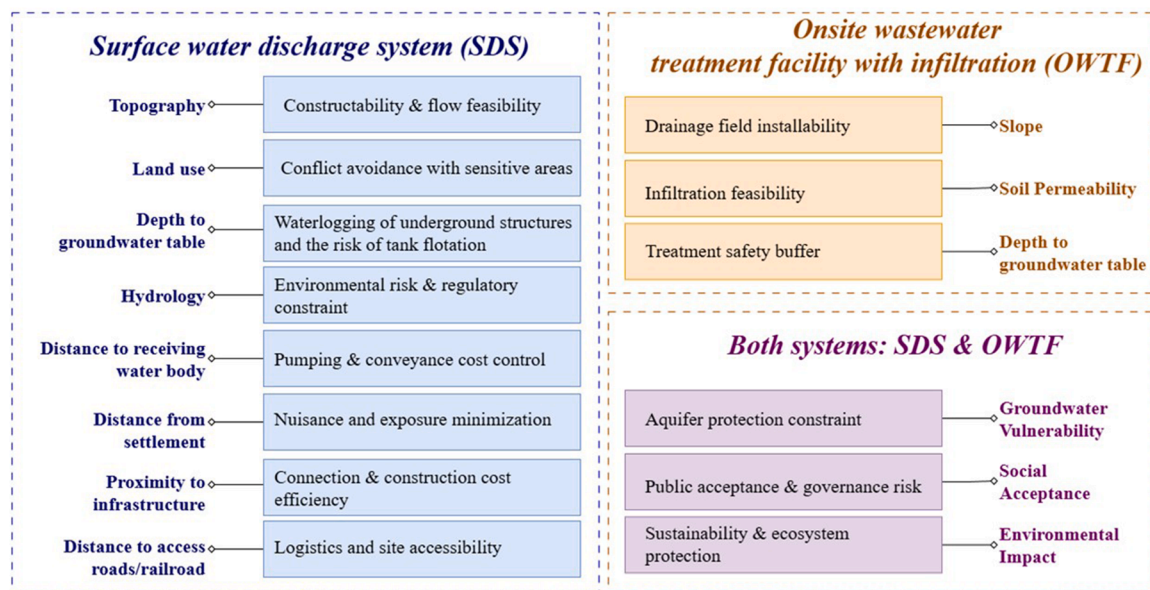


Fig. 3. Conceptual synthesis of drivers and constraints governing the suitability of SDS and OWTF in previous MCDA-based planning studies.

reflects site characteristics that favor implementation, including factors affecting feasibility, performance, and integration in the urban form. The *needs* perspective identifies areas where wastewater interventions' benefits are most needed (e.g., reducing environmental pressures, addressing public health concerns, and improving sanitation access). For each perspective, objectives were hierarchically organized into high-level objectives and sub-objectives, following VFT MCDA best practices to ensure completeness, conciseness, and non-redundancy (Marttunen et al., 2019).

2.3.2. Hierarchy construction and stakeholder validation (Workshop 1)

Objectives were organized into hierarchies (structured in fundamental and means objectives) for wastewater systems. Because infiltration-based and surface discharge systems interact differently with physical and regulatory environments, their evaluation requires distinct spatial considerations. Infiltration systems mainly depend on soil permeability, soil thickness and groundwater protection zones; whereas surface discharge systems must consider the quality and proximity of receiving waters, affecting both performance and feasibility.

Two hierarchies were therefore developed to reflect different settlement scales and treatment capacities. The first addressed infiltration-based systems (A): (A1) individual septic tanks connected to individual drain fields, and (A2) cluster-scale moving bed biofilm reactors (MBBR) connected to a polishing bed serving approximately ten households. The second focused on surface discharge systems (B): (B1) cluster-scale MBBR with surface discharge, and (B2) connection to the centralized WWTF. Each hierarchy covered technical, regulatory, socio-economic, and environmental dimensions to ensure comprehensive comparison.

For clarity and decision efficiency, the total number of objectives across the opportunities and needs perspectives was maintained between 10 and 25. This range prevents the dilution of objectives' importance and cognitive overload, as overly large hierarchies can bias weighting and complicate the decision (Marttunen et al., 2019).

The hierarchies were validated during the first stakeholder workshop involving six municipal and provincial representatives (project managers, water service directors, water treatment team leaders, and sanitary engineers). Stakeholders were selected using purposive sampling strategy combining stratified and snowball approaches to ensure representation of key institutional actors involved in wastewater management, following Haag et al. (2019). Potential participants were identified based on their roles, expertise, and direct involvement in

wastewater planning, infrastructure management, environmental regulation, or operational decision-making, and were contacted directly by email with project information and participation details. The selection process aimed to capture diverse technical and governance perspectives relevant to the study context rather than achieve statistical representativeness. Although the number of participants was limited, the selected stakeholders collectively represented the principal institutional responsibilities associated with wastewater planning and management within the study area. Further details on stakeholder identification are provided in Soleimani (2023). The online workshop, held in September 2024 using the interactive platform Miro, followed a structured elicitation process to align objectives with regulatory, technical concerns based on stakeholders' priorities.

Because articulating objectives can be challenging without guidance (Haag et al., 2019), the workshop began with individual brainstorming, followed by perspective broadening, allowing participants to consider and build on to the input generated by other actors. Six predefined categories (economic, environmental, resource, social, technical, and organizational) were then introduced to stimulate additional proposals.

Stakeholders reviewed and exchanged their objective lists, allowing them to refine and complement each other's contributions. The resulting objectives were then examined collectively to group similar ideas and identify overlaps. Finally, the master list of objectives prepared by the research team was shared with the participants, so that they could compare their proposed objectives with the literature and regulation-based master list to remove redundant or less relevant items and ensure clarity and completeness.

Following the workshop, the outputs were analyzed by the research team, and a final hierarchy was shared with the workshop participants for final validation. Stakeholders confirmed relevance, suggested refinements, and identified remaining gaps, strengthening alignment with stakeholder priorities and the structured decision-making process.

2.3.3. Geospatial data compilation

Following objectives validation in the first stakeholder workshop, geospatial datasets were compiled to operationalize criterion selection. In total, 21 geospatial data layers were collected to represent the attributes included in the analysis. To ensure accessibility and support transferability, priority was given to open-access provincial databases, complemented by local, non-public datasets specific to the case study city. Three data layers were provided by the municipality, while the

remainder were retrieved from public governmental and municipal sources. This approach supports methodological robustness, contextual relevance, and potential applicability to other urban settings.

2.4. Preference modelling

2.4.1. Value function elicitation (Expert interviews)

Value functions were elicited through expert consultations using the bisection (mid-value splitting) method (Eisenführ et al., 2010). This approach converts raw attribute values into a normalized 0–1 scale, ensuring consistent aggregation while maintaining methodological rigor. The normalization procedure ensured that heterogeneous spatial criteria expressed in different units (e.g., meters, percentages, categorical variables) could be compared and consistently integrated within the GIS-MCDA framework.

Five experts participated, representing the municipal sector (3), a public organization (1), and a private firm (1). Interviews were conducted online between October and November 2024. Objectives were grouped into thematic categories (technical, environmental, social, economic, and land-use planning), and each was assigned to an expert qualified to define the corresponding value scale based on domain expertise, knowledge, and experience in wastewater system management and planning. Four sessions of 40–60 min yielded 28 value scales. Value scales were elicited for all attributes except those directly derived from regulatory guidelines.

For continuous attributes (e.g., slope), value functions were defined using the bisection method as continuous functions, following Beutler et al. (2024), through graphical representation and iterative refinement with experts. Using the bisection method, the possible attribute values are defined to range between a minimum and maximum $[x^- \text{ and } x^+]$. Then, the decision-maker identifies an attribute value that according to their preferences sits precisely between x and x^+ , called $x_{0.5}$, so that $(x^- \rightarrow x_{0.5}) \sim (x_{0.5} \rightarrow x^+)$ and $v(x_{0.5}) - v(x^-) = v(x^+) - v(x_{0.5})$ (Eisenführ et al., 2010). For discrete attributes (e.g., land use categories), the direct method (Eisenführ et al., 2010) was applied by assigning values to attribute levels based on expert judgment. Together, these methods ensured consistent representation of continuous and categorical criteria within the decision model.

2.4.2. Preferences weighting (Stakeholder workshop 2)

Stakeholder preferences were elicited using the swing method to quantify the relative importance of decision objectives (weights). This approach captures how stakeholders prioritize when trade-offs are required, making preferences assumption explicit rather than assuming equal importance across objectives (Beutler et al., 2024).

Weight elicitation focused on lower-level objectives for four wastewater system types: infiltration-based systems (A1 at individual building scale and A2 at cluster-scale), and surface discharge-based systems (B1 at cluster-scale and B2 via centralized connection). Within each hierarchy, weights under each perspective (needs or opportunities) were normalized to sum to one. This normalization ensured internal consistency and comparability of stakeholder preferences across wastewater system scenarios and suitability perspectives.

Swing weighting method was applied during the workshop following Eisenführ et al. (2010) and implemented using the MCDA weight elicitation software of Aubert and Masson (2021) to support robustness and transparency. Participants ranked scenarios in which each objective improved from worst to best performance while others remained at their worst level. These rankings were then converted into scores from 0 (least preferred) to 100 (most preferred), with intermediate values assigned by stakeholders. Weights were calculated from stakeholder scores for both fundamental and means objectives. The weighting ensured transparent representation of stakeholder trade-offs while reducing bias in weight assignment (Aubert et al., 2020; Schuwirth et al., 2012). Further details on the weighting procedure and equations are provided in Text SI-3 (Supplementary material).

2.5. Combination rules

Spatial criteria were aggregated using a weighted linear combination (WLC) method. In GIS-MCDA, aggregation methods range from simple additive to more complex non-linear approaches such as ideal point and outranking methods (Malczewski and Rinner, 2015). WLC was selected for its simplicity, intuitive nature, transparency, and widespread use in spatial planning applications. The method assumes linearity and preferential independence among criteria, meaning that the contribution of each criterion is evaluated independently and aggregated additively. Although some interactions between spatial criteria may exist in practice (e.g., relationship between urban density, infrastructure proximity, hydrology, and environmental vulnerability), several measures were taken to reduce redundancy and excessive overlap among criteria. Objectives were structured hierarchically following VFT principals to promote non-redundancy and conceptual distinction between criteria, and each objective was associated with a specific spatial attribute representing a distinct planning dimension. Nevertheless, some degree of interaction between spatial variables cannot be fully excluded in complex territorial systems. In this context, WLC was considered appropriate for the exploratory and decision-support purpose of the study, where transparency, interpretability, and stakeholder communication were prioritized over highly parameterized interaction modelling. Future work could explore non-compensatory or interaction-sensitive MCDA approaches to better account for dependencies and synergies among spatial criteria.

Within this framework, WLC aggregates weighted performance scores across criteria to generate a composite suitability value. Higher suitability values indicate better alignment with decision objectives, yielding clear and interpretable spatial outputs that reflect both stakeholder priorities and site performance. Further details on the aggregation equation are provided in Text SI-3 (Supplementary material).

To ensure methodological consistency across scenarios, all criteria were first transformed into standardized suitability scores ranging from 0 to 1 prior to aggregation. Although some wastewater configurations shared identical objective hierarchies, value functions, and weighting structures, suitability differences between scenarios resulted from differences in the spatial representation and operationalization of criteria within each configuration.

2.6. Extreme-weight sensitivity analysis of suitability results

Sensitivity analysis was conducted using a one-at-a-time (OAT) extreme-weight sensitivity analysis to assess the influence of individual objectives on suitability results. In this framework, each objective was assigned full weight (100%) in turn, while all remaining weights were set to zero. This procedure was applied sequentially to technical, economic, environmental, and social objectives for both infiltration-based and surface discharge systems.

Sensitivity analysis remains relatively underexplored in spatial MCDA applications due to its methodological complexity and computational burden (Lacroix, 2025). In this context, the present approach aims to provide a simplified and transparent assessment to help stakeholders understand how individual objectives influence suitability maps and to support informed discussion.

Rather than representing realistic stakeholder preference configurations, the assignment of full weight to a single objective was used to isolate and visualize the maximum possible influence of each decision dimension on spatial suitability outcomes. This exploratory approach enables identification of the spatial patterns specifically associated with each objective and highlights how different decision priorities drive suitability results under extreme preference conditions. Consequently, the analysis should be interpreted as a local exploratory extreme-weight sensitivity analysis designed to characterize model behavior under single-objective dominance conditions (Malczewski and Rinner, 2015), rather than as a simulation of realistic decision-making scenarios. By

revealing objective-specific suitability patterns and trade-offs, the approach supports interpretation of model behavior, transparency in stakeholder discussions, and understanding of the relative influence of competing planning objectives.

3. Results

3.1. Development and validation of objective hierarchies

Two final hierarchies of objectives were developed from the master list (Tables SI-2 and SI-3 in Supplementary material) to reflect the opportunities and needs across wastewater strategies. Hierarchy (A) addresses infiltration-based OWTF (Fig. 4), while hierarchy (B) targets SDS and centralized connection options (Fig. 5). Most objectives from the master list were validated by stakeholders and were independently identified during elicitation activities, indicating strong convergence between literature and stakeholder perspectives. Five additional sub-objectives were proposed during the workshop; however, these were excluded due to the lack of suitable spatial data for operationalization.

An exclusion exercise confirmed the relevance of retained objectives as none were considered by participants as redundant or irrelevant, supporting the completeness and appropriateness of the final hierarchies.

3.2. Preference modelling

Preference weighting was elicited during the stakeholder workshop (Section 2.4.2). For OWTF (hierarchy A), highest weights were assigned to *maximizing the distance from drinking water supply wells* (0.17), *minimizing sewer and treatment plant overload* (0.16), and *reducing groundwater vulnerability* (0.15). These priorities highlight an emphasis on water protection and infrastructure resilience (Figures SI-1 and SI-2). In contrast, environmental co-benefits received the lowest weights, including *minimizing heat island effects* (0.04), *reducing overflows* (0.06), and *maximizing access to green spaces* (0.07).

For SDS (hierarchy B), the most influential objectives were *maximizing distance from drinking water supply wells* (0.17), *ensuring system adaptability to development density* (0.16), and *minimizing overflows* (0.16), reflecting a focus on water pollution control and system

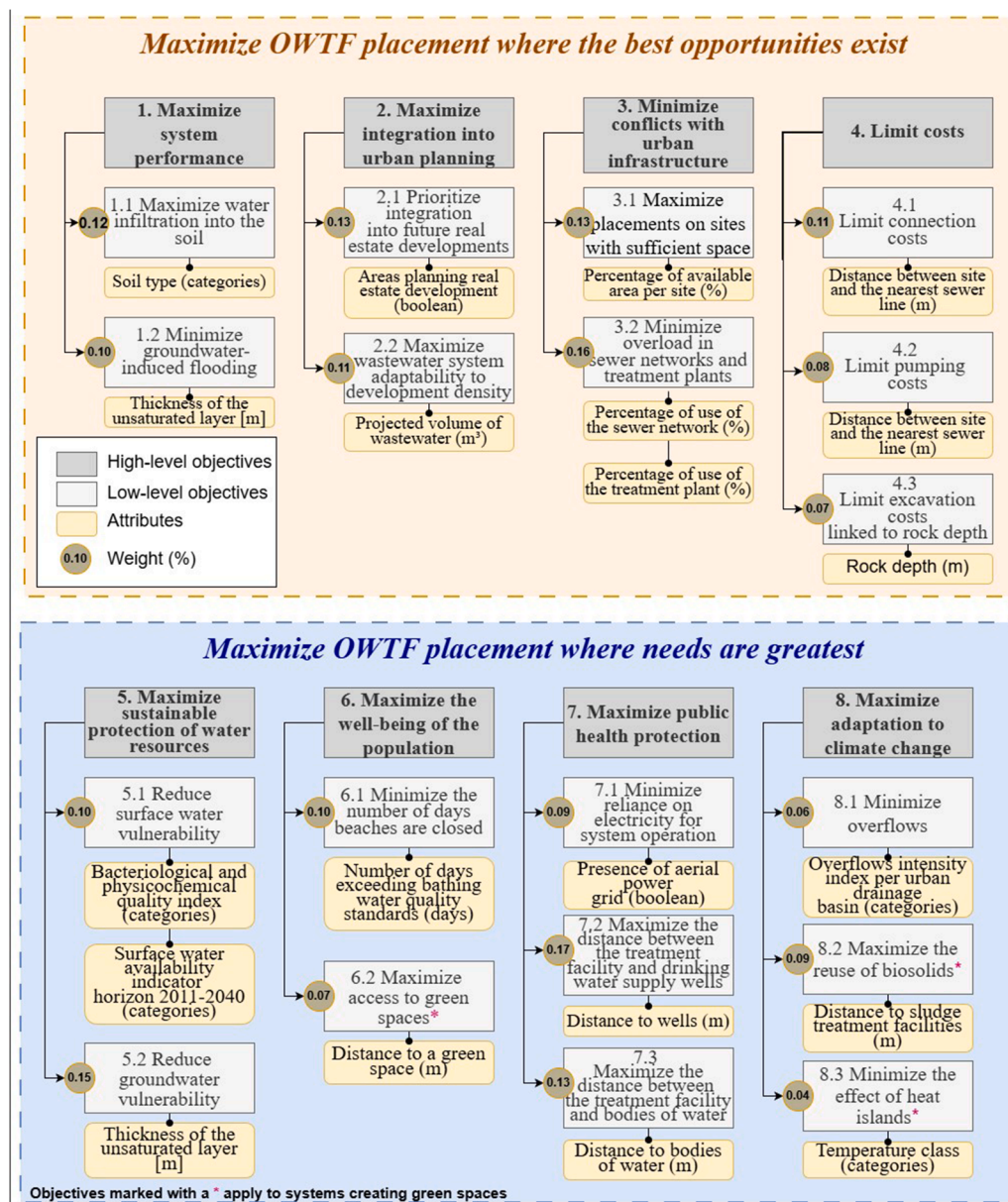


Fig. 4. Hierarchy of objectives for OWTF based on the opportunities and needs perspectives.

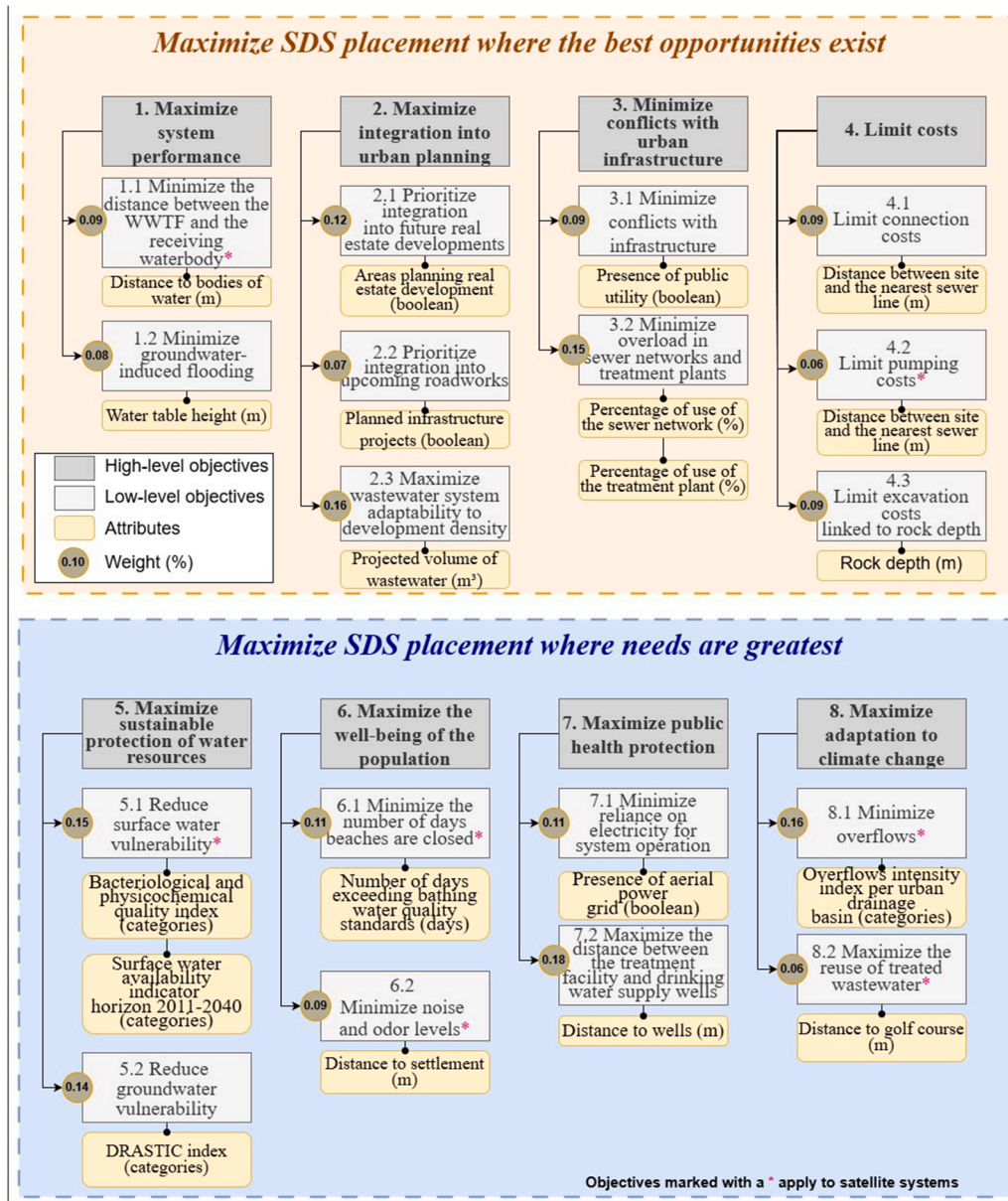


Fig. 5. Hierarchy of objectives for SDS based on the opportunities and needs perspectives.

performance under varying population densities (Figure SI-3 and Figure SI-4). Lower weights were attributed to *wastewater reuse* (0.06), *limiting pumping costs* (0.06), and *integrating with upcoming roadworks* (0.07), suggesting that economic and planning considerations played a comparatively minor role in preference weighting. The complete set of value functions and weights is provided in Tables SI-4 to SI-7.

3.3. Combination rules: creating suitability maps

Fig. 6 maps suitability for infiltration-based wastewater systems under both opportunities (Fig. 6a and 6c) and needs (Fig. 6b and 6d) perspectives. The analysis covers a central low-density residential area of single-family housing and two projected development zones: site (i) in the southwest (60 dwellings/ha) and site (ii) in the northeast (21 dwellings/ha).

Fig. 7 presents the corresponding suitability maps for surface discharge systems under the same perspectives and spatial context.

Although A1 and A2 (and similarly B1 and B2) rely on the same objective hierarchy, weights, and value functions, the resulting

suitability maps differ because several criteria are evaluated using scenario-specific spatial representations. Variables such as proximity to infrastructure, available space, or environmental benefits are derived from datasets or spatial configurations that differ between decentralized, centralized, and hybrid systems. In hybrid configurations (A2 and B2), some criteria explicitly integrate both local and centralized components, which modifies their spatial representation compared to purely decentralized (A1) or centralized (B1) systems. As a result, even with identical weights and value functions, the underlying spatial inputs differ, leading to distinct suitability outcomes.

Opportunity-based suitability is generally higher in site (i) than in site (ii) across all systems. For OWTF (A1, Fig. 6a), favorable conditions in site (i), reflected by suitability scores above 0.60, mainly reflect permeable soil and sewer networks operating near capacity. Hybrid systems (A2, Fig. 6c) also show high opportunities (scores above 0.70) in denser zones (site (i)), where installation space and sustainability benefits converge. For SDS, both centralized (B1, Fig. 7a) and hybrid (B2, Fig. 7c) configurations exhibit higher opportunities near existing sewer infrastructure or potential discharge points such as rivers.

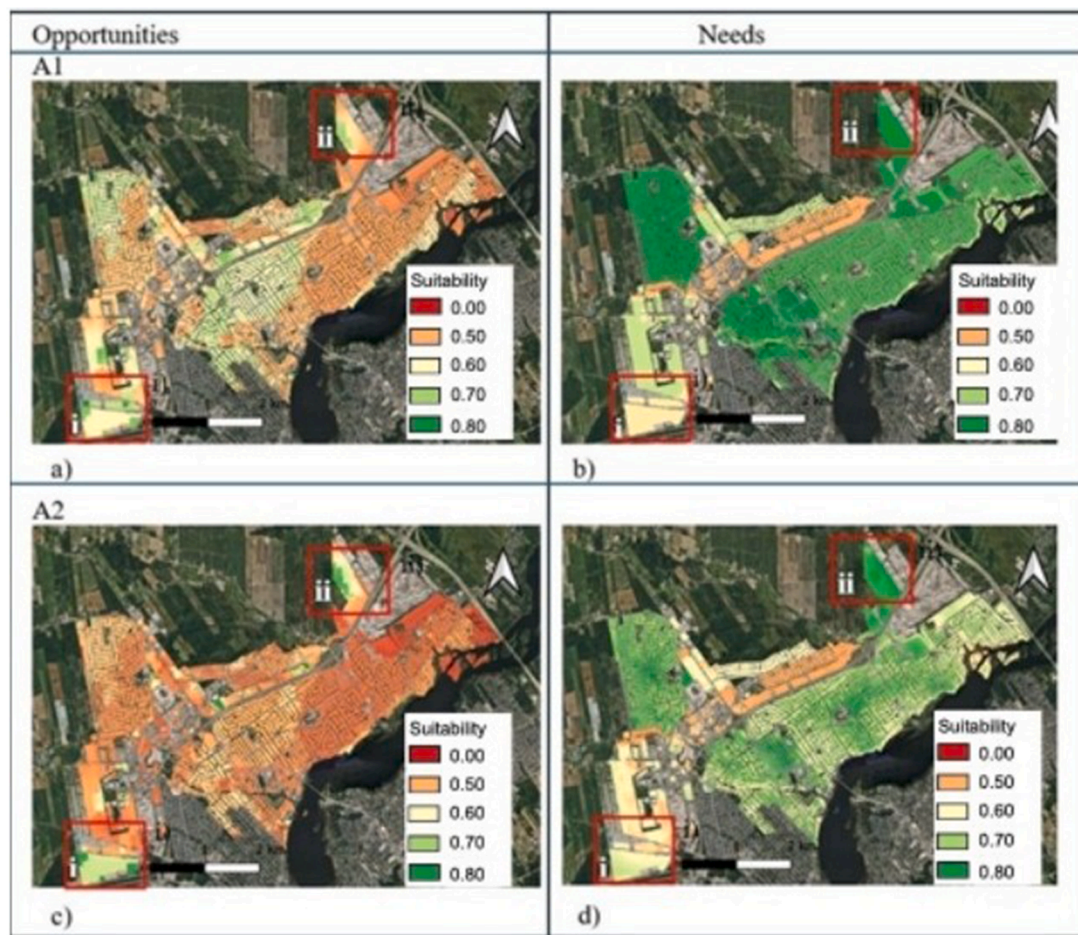


Fig. 6. Suitability maps for decentralized infiltration systems (A1) and hybrid infiltration systems (A2) evaluated under opportunities and needs perspectives.

In contrast, need-based suitability is generally higher in site (ii) for all systems. Elevated needs for OWTF (A1 and A2) (Fig. 6b and 6d), reflected by suitability scores near 0.80, are driven by overflow intensity, bathing water quality exceedances, and bacteriological and physicochemical pollution levels, with additional contribution from green spaces proximity and urban heat-islands mitigation for hybrid systems. Among SDS, hybrid configurations (B2, Fig. 7d) show the highest need-based suitability (near 0.80) in site (ii), while centralized systems (B1, Fig. 7b) maintain moderate to low values across both sites (scores near 0.50).

Overall, hybrid infiltration systems (A2) achieve the highest suitability in site (i), where wastewater generation and urban resilience objectives align. In site (ii), where infiltration is limited but discharge access is favorable, hybrid SDS (B2) perform best. Centralized SDS (B1), although technically feasible, show limited alignment with spatially distributed needs.

3.4. Extreme-weight sensitivity analysis of suitability results

Figures SI-5 and SI-6 present the suitability of OWTF (A1, A2) for opportunities and needs objectives. For opportunities, site (i) shows low suitability under *Maximize system performance* due to unfavorable water table height and soil type. In contrast, under *Limit connection costs*, it performs better because of the absence of a nearby sewer network and distances greater than 1000 m, although high pumping costs. Regarding *Maximize integration into urban planning*, A1 is unsuitable in sites (i) and (ii) because projected wastewater flows exceed its capacity, while A2 remains suitable owing to its higher treatment capacity.

For needs-related objectives, A1 and A2 show high suitability for

Maximize sustainable protection of water resources and *Maximize public health protection*, supported by favorable bacteriological quality, DRASTIC index, and distance to wells and surface waters. Under *Maximize the well-being of the population*, suitability is high for the *Minimize the number of days beaches are closed* objective, as infiltration systems avoid surface discharges. For *Maximize access to green spaces*, A2 is less needed due to the existing high green space density. Under *Maximize adaptation to climate change*, infiltration systems perform well for *Minimize overflows*, although A2 shows low suitability for *Maximize the reuse of biosolids* because of the absence of nearby sludge recovery facilities.

Figures SI-7 to SI-9 present results for surface discharge systems. For opportunities, B2 shows high suitability for *Minimize the distance between the WWT and the receiving waterbody* near tributary rivers, but rivers remain distant from sites (i) and (ii). Under *Maximize integration into urban planning*, both B1 and B2 perform well except for *Prioritize integration into upcoming roadworks* and *Minimize conflicts with existing urban infrastructure*, where B2 shows lower suitability. For *Minimize overload in sewer networks and treatment plants*, B1 performs poorly near saturated sewers, while B2 is less affected.

For the needs objectives, B2 shows high suitability for *Maximize sustainable protection of water resources*, *Maximize public health protection*, *Maximize the well-being of the population*, and *Maximize adaptation to climate change*, but lower suitability for *Maximize the reuse of treated wastewater* due to the absence of reuse sites. In contrast, B1 performs poorly across most needs-related objectives, reflecting limited responsiveness to territorial priorities. Its spatial pattern is the inverse of that observed for B2 and A-type systems, which offer greater flexibility and better alignment with protection and adaptation goals.

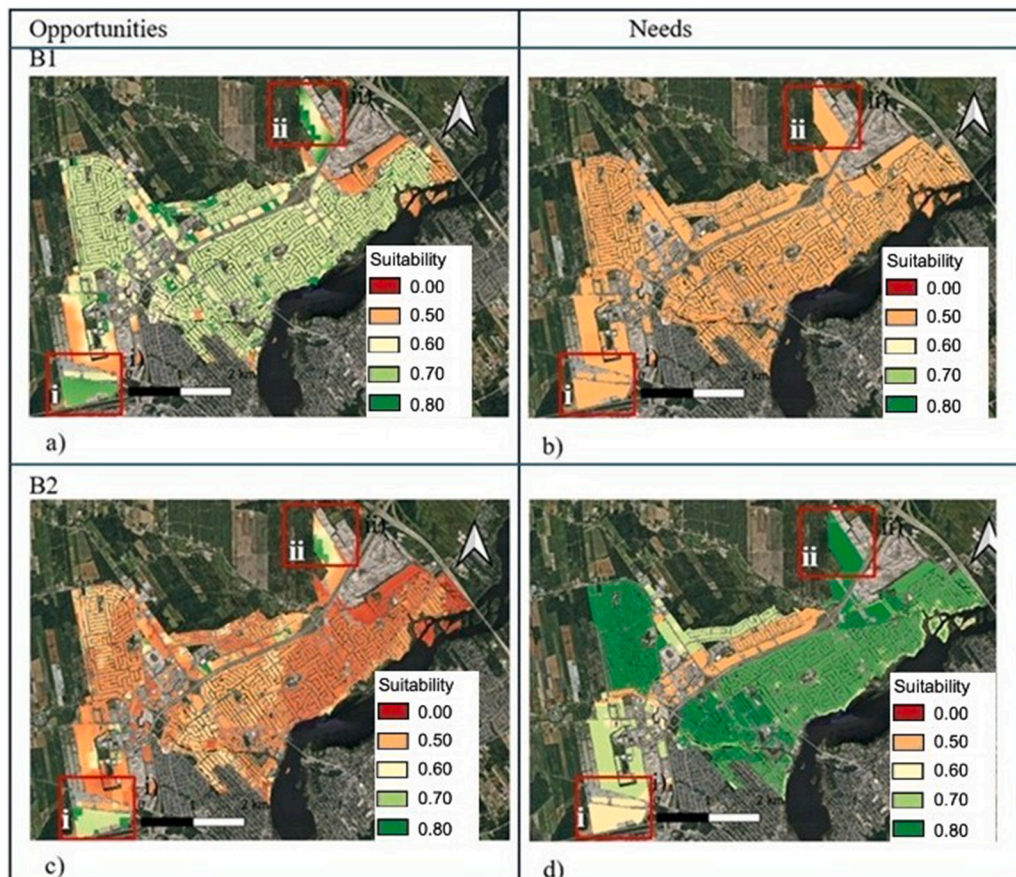


Fig. 7. Suitability maps for centralized surface discharge systems (B1) and hybrid surface discharge systems (B2) evaluated under opportunities and needs perspectives.

4. Discussion

4.1. Spatial trade-offs between implementation opportunities and territorial needs and implications for planning choices

The findings show that urban morphology and environmental vulnerability jointly shape wastewater system suitability, revealing a clear tension between implementation feasibility (opportunities) and territorial urgency (needs). High-density zones favor semi-collective and hybrid systems (A2, B2), which leverage concentrated wastewater flows and spatial efficiency, while low-density and peri-urban areas remain more compatible with decentralized OWTF (A1) due to greater land availability and reduced network extension needs. This density-driven differentiation is consistent with previous studies showing that compact urban forms favor shared or collective treatment solutions, while dispersed settlements benefit from decentralized or on-site systems (Saadatinavaz et al., 2024; Milićević et al., 2024).

Areas experiencing elevated environmental and sanitary pressures (e.g., frequent overflow, degraded water quality) exhibit higher need-based suitability for decentralized and hybrid configurations (A1, A2, B2). This aligns with non-spatial MCDA and urban water planning studies, highlighting the role of alternative and hybrid systems in reducing pollutant loads, relieving pressure on centralized infrastructure, and improving environmental and public health outcomes (Solomon et al., 2025; Sha et al., 2024; Duque et al., 2024). Together, these results provide spatial evidence that centralized systems alone are often insufficient for heterogeneous urban and peri-urban contexts. More specifically, the comparative analysis indicates that hybrid systems (A2 and B2) repeatedly achieve stronger suitability across multiple objectives and spatial contexts than purely centralized configurations

(B1), particularly under the need-based perspective. While decentralized OWTF (A1) remain advantageous in low-density and peri-urban sectors, hybrid systems appear to provide the most consistent balance between infrastructure feasibility, environmental protection, and adaptation capacity across the study area. Accordingly, no single option emerges as universally dominant across the study area; suitability remains context-dependent, supporting place-based and hybrid strategies.

From a planning perspective, hybrid infiltration (A2) and hybrid SDS (B2) represent the most promising options for sites (i) and (ii), offering a pragmatic compromise between feasibility and needs. Centralized SDS (B1) remain feasible near existing networks, but discussions with municipal engineers pinpointed substantial economic and operational constraints, particularly for site (i), where implementation would require approximately 3 km additional sewer and new pumping facilities. Similar cost and lock-in effects associated with extending centralized networks have been documented in urban water infrastructure planning (Samuel et al., 2016).

A diversified strategy, including partial disconnection and the deployment of decentralized infiltration systems (A1) in under-performing sectors, was considered but deemed impractical by stakeholders within the current planning context. This stakeholder position contrasts with the spatial suitability results, which indicate that decentralized and hybrid systems (A1, A2, and B2) often align more closely with territorial needs and environmental protection objectives than the fully centralized configuration (B1), particularly in peri-urban and infrastructure-constrained sectors. The persistence of preference toward centralized approaches despite these findings reflects broader innovation barriers and path dependency in the sanitation sector, where familiarity with conventional centralized systems limits the adoption of alternatives despite their potential benefits (Hacker and Binz, 2021). In

this sense, the GIS-MCDA results not only identify technically suitable areas but also reveal tensions between spatial suitability outcomes and prevailing institutional planning practices.

Suitability values across the new development areas remain relatively close (typically 0.6–0.8), partly due to the compensatory nature of the WLC model. In such a model, poor performance on one criterion can be offset by strong performance on others through additive aggregation, so that the overall score reflects a balance of trade-offs rather than extreme performances on individual criteria. Consequently, alternatives with contrasting strengths may converge toward similar global suitability values, and systems exhibiting critical weaknesses in specific dimensions may still achieve relatively high aggregated suitability scores. This limitation is particularly relevant for hybrid systems, whose diversified configurations may simultaneously perform strongly on some objectives while underperforming on others. As a result, aggregated suitability maps should not be interpreted as indicating uniformly favorable performance across all criteria, but rather as reflecting compromise solutions across competing objectives. To mitigate this limitation, the interpretation of suitability maps was complemented by objective-specific sensitivity analysis, allowing identification of the spatial influence of individual decision dimensions.

Future work could additionally explore partial compensatory methods (where the level of compensation between criteria is elicited as a preference from stakeholders) and non-compensatory MCDA approaches (e.g., outranking or rule-based methods) that limit trade-offs and penalize poor performance on critical criteria (Lacroix, 2025; Drobne and Lisec, 2009; Chen, 2013; Ezbakhe and Perez-Foguet, 2018; Alvarado et al., 2016). Comparing compensatory and non-compensatory aggregation schemes would assess the robustness of these patterns and clarify model effects from spatial signals.

Finally, the proposed GIS-MCDA framework should be viewed as a decision-support tool rather than a prescriptive optimizer. It delineates feasible solution spaces and makes trade-offs explicit among cost, environmental protection, infrastructure constraints, and adaptability, in line with value-focused and multicriteria decision analysis principles (Linkov et al., 2020). In this perspective, the results support a portfolio logic in which different wastewater system types are combined across the territory according to local conditions, with hybrid solutions playing a key role as compromise options between feasibility constraints and protection or adaptation needs.

4.2. Insights from extreme-weight sensitivity analysis

The OAT extreme-weight sensitivity analysis demonstrates that suitability outcomes are strongly shaped by weight attribution, confirming that spatial prioritization in MCDA is inherently shaped by value judgements. Objectives related to environmental protection, infrastructure constraints, and cost factors generate pronounced spatial contrasts and play a key role in differentiating between sites and system configurations. In contrast, objectives associated with public health protection, well-being of the population (e.g., minimizing beach closure days), and access to green spaces tend to produce more homogenous suitability patterns across the study area, resulting in limited differentiation in site prioritization. This finding aligns with previous MCDA studies showing that weighting often exerts a decisive influence on aggregated suitability maps, particularly when objectives compete (Sallwey et al., 2019; Rahman et al., 2012; Hani et al., 2023).

Extreme-weight sensitivity analysis also serves as a governance and transparency tool by making explicit which value judgments matter most in shaping decision outcomes. In this study, the stable performance of system (B2) across multiple priority configurations reflects its adaptability to both territorial opportunities and needs. Whereas system (B1) aligns poorly with local needs and offers limited flexibility. Such contrast helps distinguish structurally robust option from those whose performance depends strongly on specific preference assumptions, a key element of accountable decision-making.

The OAT approach reveals the internal trade-offs within the model, enhancing results interpretability and supporting deliberation among stakeholders. By showing how changes in weights shift spatial priorities and system rankings, extreme-weight sensitivity analysis provides a concrete basis for negotiating competing objectives—such as cost containment, environmental protection, and infrastructure constraints—rather than treating the final suitability maps as fixed technical outputs. In this sense, extreme-weight sensitivity analysis strengthens both the methodological stability and decision relevance in participatory planning contexts.

4.3. Strengths, limitations, and transferability of proposed GIS-MCDA approach

The proposed GIS-MCDA framework presents several key strengths. It enables a structured and spatially explicit comparison of alternative wastewater system configurations across scales, integrates heterogeneous technical, environmental, economic, and social criteria, and supports participatory decision-making by incorporating stakeholder preferences. The approach also promotes transparency and traceability by making assumptions, constraints, and trade-offs explicit, thereby facilitating informed discussion among decision-makers.

Stakeholder discussions emphasized that the suitability maps provided a useful basis for spatial reflection and strategic dialogue. By making constraints explicit, structuring comparison between alternatives, and requiring stakeholders to justify choices, the framework supports more transparent and traceable planning processes. In this sense, the approach complements, rather than replaces, detailed engineering design and cost optimization studies. The interpretation of suitability maps in the present study remains primarily exploratory and comparative in nature. Future work could complement visual interpretation with additional spatial statistical analyses to further quantify spatial contrasts and clustering patterns among suitability outcomes.

The proposed suitability assessment however does not represent the physical coordination required between system components, particularly for configurations involving sewer connections or centralized treatment. Each location is evaluated independently, without explicitly representing the spatial organization needed to link sewer networks, treatment infrastructure, and discharge points. This limitation may particularly impact the analysis of centralized SDS (B1), whose feasibility depends not only on local site conditions but also on network connectivity and proximity to supporting infrastructure. Such constraints are well recognized in raster-based or location-by-location GIS-MCDA approaches, which are primarily designed for strategic screening rather than detailed infrastructure layout or network optimization (Lacroix et al., 2024; Medrano, 2021). Nevertheless, the framework can support preliminary identification of areas where more detailed engineering analysis should be prioritized. Future developments could strengthen practical applicability by coupling the GIS-MCDA framework with sewer network modelling, hydraulic simulations, graph-based connectivity analysis, or infrastructure optimization approaches capable of explicitly representing physical coordination between system components. Integrating dynamic infrastructure constraints, conveyance requirements, pumping energy, and phased network expansion scenarios would allow the framework to move beyond strategic spatial screening toward more operational planning support. Such integration would be particularly relevant for evaluating hybrid systems, where performance depends strongly on coordination between decentralized and centralized infrastructure components.

Data availability constrained the operationalization of some stakeholder-proposed objectives, meaning that the assessment partly reflects the current state of available geospatial data rather than the full set of planning priorities. This common limitation is known in applied spatial decision-support studies as reviewed by Gontte (2024). Several objectives proposed during stakeholder discussions could not be spatially represented with sufficient resolution or methodological

consistency and were therefore excluded from the final analysis. Although these objectives were considered relevant by participants, their operationalization would have required spatial datasets or indicators that were unavailable, incomplete, or difficult to standardize within the GIS-MCDA framework. The exclusion of these objectives may have influenced the resulting suitability landscapes by reducing the representation of certain local concerns and contextual dimensions. In particular, omitted objectives related to governance, operational management, social acceptability, or long-term implementation constraints could have altered the spatial prioritization of some wastewater configurations, especially hybrid systems whose performance depends on coordination across multiple infrastructures and stakeholders. As a result, the final suitability maps primarily reflect objectives that could be robustly spatialized and quantified, potentially favoring criteria associated with physical feasibility, environmental vulnerability, and infrastructure proximity.

The definition of weights and value functions, while grounded in stakeholder elicitation, reflects the inherently preference-based nature of MCDA. The integration of stakeholder perspectives constitutes a key strength of the approach, allowing decision-making to account for context-specific priorities and values. Yet, MCDA outcomes are known to depend on both the composition of the stakeholder group and the elicitation process (Williams and Fang, 2019). In the present study, the participatory process involved a limited but purposefully selected group of actors, mainly from municipal and provincial technical institutions. Stakeholders were selected using purposive sampling strategy to ensure representation of key institutional responsibilities related to wastewater planning, infrastructure management, environmental regulation, and operational decision-making within the study area. These participants were well positioned to assess technical and regulatory constraints relevant to strategic wastewater planning; however, they may not fully represent broader community perspectives, such as those of residents or environmental non-governmental organizations, regarding the relative importance assigned to certain objectives. The objective of the participatory process was therefore not statistical representativeness, but rather the integration of informed technical and governance perspectives relevant to the decision context. The extreme-weight sensitivity analysis partly addresses this limitation by illustrating how alternative weighting assumptions affect spatial outcomes. Future applications could broaden stakeholders' involvement to capture a wider diversity of values.

While the proposed framework is generic in structure, the results are case-specific and transferability to another urban context, especially in a different region, requires careful adaptation, potentially including re-eliciting preferences, recalibrating some value functions, and adapting spatial indicators to local regulatory, environmental, and infrastructural contexts. Although the GIS-MCDA workflow, participatory structure, and hierarchical decision framework are transferable, several assumptions embedded in the analysis reflect the Quebec planning and regulatory context, including wastewater discharge regulations, groundwater protection requirements, infrastructure design practices, and land-use planning constraints. Because these regulatory and institutional conditions may differ substantially across countries and regions, future applications may require recalibration of value functions, spatial indicators, environmental thresholds, and stakeholder preferences to ensure contextual relevance and methodological consistency. In addition, climatic conditions, urban morphology, infrastructure density, governance structures, and public health priorities may influence both the relative importance of objectives and the spatial interpretation of suitability results. Consequently, the framework should be interpreted as a transferable, adaptable decision-support methodology rather than a universally applicable suitability model. Future applications across contrasted international contexts would help further evaluate the robustness, adaptability, and scalability of the proposed GIS-MCDA approach.

Finally, the current implementation provides a largely static

representation of suitability and does not capture dynamic processes such as urban growth, climate change impacts, or infrastructure aging, under different scenarios. However, the hierarchical and the modular design of the framework offer opportunities for future extensions toward scenario-based or time-dependent analyses.

4.4. Contributions and future extension of the GIS-MCDA framework

Beyond its immediate planning applications, this study makes several original contributions to spatial decision-support for wastewater system planning. First, it explicitly distinguishes between opportunity-based and need-based perspectives within a GIS-MCDA framework, thereby bridging feasibility-driven spatial screening with protection- and benefit-oriented territorial priorities—an aspect that is rarely addressed in existing spatial suitability studies. Second, the development of system-specific objective hierarchies for infiltration-based and surface-discharge systems moves beyond generic criteria sets and allows the decision structure to reflect fundamentally different planning logics. Third, by combining stakeholder-based preference elicitation with the spatial operationalization of technical, environmental, and public health objectives, the framework connects non-spatial MCDA traditions with GIS-based planning tools in a unified, transparent approach. Finally, by framing the outputs as decision-support rather than prescriptive solutions, the study positions GIS-MCDA as a tool for structured dialogue, negotiation, and exploration of trade-offs rather than a technocratic optimization instrument.

From a research perspective, several extensions can further strengthen the approach. Future work could integrate climate change scenarios to assess the robustness of spatial suitability patterns under evolving hydrological and demographic conditions, combine the framework with cost–benefit or life-cycle assessment to better capture economic and environmental trade-offs, and incorporate additional environmental risk indicators, such as hazard quotient (HQ)-based approaches used in aquatic hazard assessment studies, to better represent the potential public health and ecological impacts associated with wastewater contaminants (Nateq et al., 2025). Social acceptance indicators as well as governance and institutional constraints could also be integrated to better reflect real-world implementation challenges. In addition, applying the framework to other urban contexts, to rural and peri-urban gradients, and under different regulatory regimes would allow testing its transferability and refining its structure across contrasted planning environments.

5. Conclusion

This study examined the extent to which a GIS-based, value-focused MCDA framework can improve the transparency, consistency, and spatial relevance of trade-off analysis among centralized, decentralized, and hybrid wastewater systems. System-specific hierarchies of objectives were developed, operationalized through spatial indicators and value functions, and implemented within a spatially explicit decision-support tool validated through stakeholder input.

The results highlight that:

- Suitability patterns are jointly controlled by urban form, environmental vulnerability, and infrastructure constraints, and that no single system type is optimal across the study area. Hybrid configurations emerge as robust compromise options, whereas purely centralized solutions display limited alignment with spatially distributed needs.
- The distinction between opportunity-based and need-based perspectives proved critical for revealing planning trade-offs and supporting context-sensitive system portfolios rather than prescriptive solutions.
- Extreme-weight sensitivity analysis shows that suitability results vary substantially across objectives within a given decision

perspective (needs or opportunities), highlighting how each objective individually shapes the resulting suitability patterns. This supports a clearer interpretation of objective-specific influences on suitability maps and reinforces the framework's contribution to transparency and informed deliberation in decision-making.

- The proposed approach should be understood as a strategic screening tool supporting dialogue among stakeholders rather than a substitute for detailed engineering design.

The framework provides a structured and transferable basis for integrating stakeholder values with spatial analysis and for supporting more transparent and robust wastewater planning under competing objectives. In a context heavily influenced by existing urban infrastructure lock-in, at a time when aging, saturated wastewater systems require urgent intervention, this easily accessible tool opens a dialogue among municipal stakeholders to explore alternative wastewater solutions with potential impacts on urban resilience over decades.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT in order to improve readability and language clarity. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

CRediT authorship contribution statement

Raja Kammoun: Writing – review & editing, Visualization, Investigation. **Olivier Sayegh-Lévesque:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martijn Kuller:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Leila Eamen:** Writing – review & editing, Investigation, Data curation. **Dominique Claveau-Mallet:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Françoise Bichai:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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Supplementary materials

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Data availability

The data that has been used is confidential.

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