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Planning Decision Support System for the Transition to Circular and Green Scaled Urban Water System

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Abstract

Climate change and urbanization are intensifying pressures on urban water, energy, food, and ecosystem resources, manifesting in more severe challenges—such as floods and water scarcity—that threaten urban well-being. To address these issues, cities should transition from conventional water management to circular schemes that recover resources and mimic natural processes to restore the water cycle. This study introduces a planning support system using GIS and MCDA to optimize the siting of Water Management Units (WMUs) designed for circularity and greening, integrating supply, wastewater, and stormwater systems. The methodology uses R and QGIS to integrate 15 green infrastructure and 10 circularity criteria. The prioritization framework supports decisions at macro (neighbourhoods) and micro (allotment) scales, promoting equitable resource distribution and maximizing environmental benefits. The case study in Girona, Spain, explores 62 city sectors and 997 allotments to assess context suitability and identify priority sites. Transition scenarios are then analysed to evaluate their impact on the water-energy-food-ecosystem nexus and the social dimension of hydrosocial urban systems. The findings provide actionable insights for urban planners and policymakers, supporting the shift to resilient, circular urban water systems.

Highlights

- PDSS for integrated management of supply, wastewater, and stormwater.
- GIS-MCDA using hydrosocial data at two spatial levels for siting scaled WMUs
- Scenario planning for circular and greener UWSs, leveraging economies of density.

Introduction

Urban areas increasingly face water challenges, yet planning for sustainable urban water systems (UWSs) often remains reactive, responding to disasters rather than preventing them. Examples such as Singapore and Windhoek (Namibia) demonstrate the effectiveness of water reuse systems for long-term water security, while China's sponge cities and decentralized non-potable reuse in Australia and Japan arose in response to flooding and drought crises, respectively (Wilcox et al., 2017). The Water-Energy-Food-Ecosystem (WEFE) nexus offers a comprehensive framework to balance resource use, sustainability, and equity (Estoque, 2023). Planning Decision Support Systems (PDSS) should integrate systems-thinking principles to assess synergies and trade-offs in UWS design strategies, while accounting for the cross-sectoral impacts of interventions (Simonovic, 2021). GIS-MCDA is increasingly used to evaluate environmental, economic, and social criteria both spatially and visually, while enabling stakeholder input to align solutions with community values and resilience goals. Current PDSS tools often focus on stormwater (Bach et al., 2020; Kuller et al., 2017) or on hydraulic impacts of decentralized reuse (Rauch et al., 2017), with recent examples ranging from spatial green infrastructure suitability mapping to cost–optimization of water reuse networks (Guo & Englehardt, 2015; Kavvada et al., 2018). While effective within their respective domains, many existing tools focus on isolated aspects rather than integrating all water streams—supply, wastewater, and stormwater—along with the socioeconomic and environmental dimensions of hydrosocial urban systems (Wesselink et al., 2017). Novel PDSSs should address these gaps, considering social vulnerabilities and environmental justice from the planning stage.

In contrast to SSANTO (focus on WSUD siting) and UrbanBEATS (a WSUD scenario generator), our PDSS addresses a dual objective—circularity and greening—and integrates three water streams without requiring hydraulic models. Unlike Kavvada et al. (2018), who optimize reuse networks for a specific non-potable reuse scenario or Bouziotas et al., (2019), whose UWOT model simulates all water flows through a calibrated tree structure, our approach prioritizes potential sites city-wide, across scales, and for multiple circular strategies (e.g., non-potable reuse for irrigation or flushing, rainwater harvesting, thermal energy recovery, fertigation, and water cycle restoration via green infrastructure). It avoids detailed technological specifications and simulation dependencies, thus enabling early-stage planning and rapid screening.

This research aims to develop a GIS-MCDA-based decision support system to facilitate the proactive transition of UWSs. By prioritizing the siting of WMUs at different spatial scales and integrating key contextual factors, this approach supports city planners in adopting a modular transition process that capitalizes on economies of density (Eggimann et al., 2016). Scaled WMUs are employed to promote circularity and urban renaturing, delivering context-specific solutions to mitigate water-related challenges and enhance overall health of all living beings.

Methodology

The proposed methodology follows a structured approach to identify optimal sites for WMUs (Figure 1) and comprises nine steps structured across two phases. Steps 1–4 (green arrow) reflect completed work, including objective framing, mapping of hydrosocial context variables, integration into a multicriteria matrix via QGIS and R, and GIS-based MCDA for prioritizing candidate sites. Steps 5–9 (grey arrow) represent ongoing or future research. These include the development of a water scheme catalogue, construction of a relational database linking site characteristics and scheme suitability, clustering for optimal scale deployment, scenario building, and performance assessment of transition strategies. The required steps and sub steps are detailed below:

(i) **Objective Definition:** Establishing goals for scaled water management units with a focus on circularity and greening objectives.

(ii) **Selection of Relevant Hydrosocial Variables:** It is considered hydrological-hydraulic, socioeconomic and environmental variables to represent the context in sector (neighbourhood) and allotment scale (Arnaud et al., 2024), initially identifying 25 relevant spatial criteria (15 related to greening needs and 10 for circularity potential) spanning hydrological, environmental, and social dimensions;

(iii) **Multicriteria Mapping:** treating the data and building the decision matrix considering the following sub steps:

a. Determination of criteria set.
b. Data collection and aggregation.

c. Selection of MCDA method, for which, it was chosen the Priority Observed from the Presumption of Gaussian Attitude of Alternative, as described by (dos Santos & dos Santos, 2021) method.
d. Construction of the decision matrix.
e. Normalization of the data.

(iv) **Priority sites definition using GIS-MCDA**, considering the sub steps:

a. Weighting the criteria, with weights derived from the literature based on Arnaud et al., 2024) which analysed 51 peer-reviewed articles to establish qualitative associations between context criteria of scale suitability considering circular and green design strategies of water systems.
b. Generation of priority maps for various scales for each objective (circularity and greening) and considering both.
c. Sensitivity analysis: The sensitivity analysis evaluates the effect of each criterion on the outcome and checks for highly correlated variables, which can be combined into composite indices, trough collinearity studies conducted based on Principle Component Analysis (PCA) to simplify the model without significant loss of information.

(v) **Building the Water Schemes Catalogue**: Evaluating water pathways and greening applications, considering energy and other resources surpluses.

(vi) **Developing a Relational Data Base:** Linking water schemes with urban water challenges, feasible land uses, and other contextual constraints to guide the siting of circular and/or green interventions.

(vii) **Clustering neighbourhood allotments** Grouping urban areas suitable for the same water schemes to identify optimal water management scales (or decentralization degrees) of implementation. Constraints related to elevation and distances from source and reuse location are considered.

(viii) **Scenario Development:** The scenarios definition will be very similar to the methodology proposed by Calle et al.(2023), estimating the population and area covered by scaled WMUs with circular and greening objectives. Population of each city sector is given by the municipal database, while the Spanish Cadastre provides information regarding the type of usage of each property within the buildings (e.g.: industrial, commercial, tourism, residential). These inputs are used for the estimation of wastewater for non-potable (e.g.: flushing and irrigation demands) and potable reuse potentials. Scenarios incorporate varying percentages of reused water and stormwater management capacity via green infrastructure.

(ix) **Impact Assessment**: Measuring the influence of selected interventions on the WEFE Nexus and hydrosocial systems. Performance is assessed using generalized metrics from the *water scheme catalogue*, covering aspects such as water reuse volumes, energy use, nutrient recovery, food production, and ecosystem service enhancement.

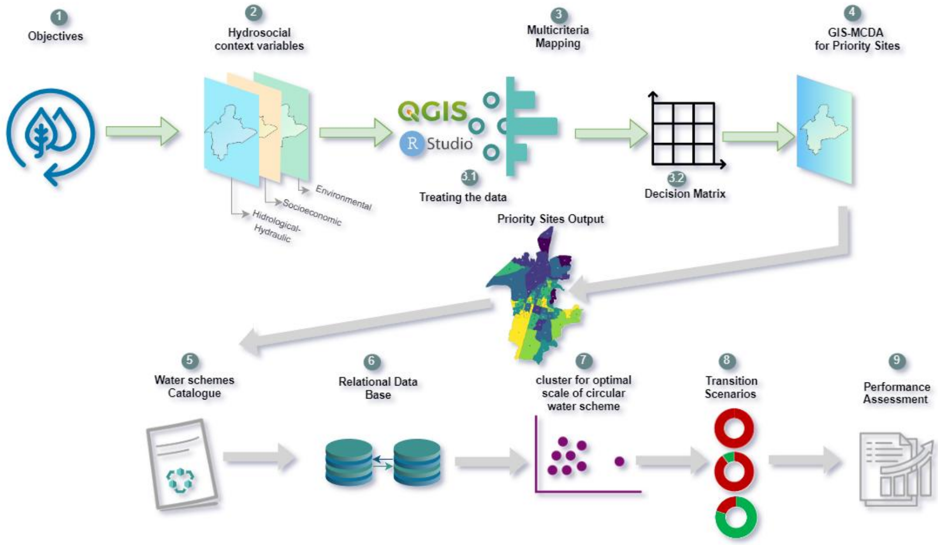

Figure 1. Methodology for the PDSS for the transition to circular and green scaled UWSs.
Legend: Steps 5-9 (grey arrow) are ongoing work; and shown here to demonstrate model extensibility and still requires validation.

Case study

The study area is Girona (Figure 2), a city in northeast Catalonia, Spain, with 104,038 inhabitants (2023), an area of 39.12 km², a population density of 2,659.5 hab./km², and with four main rivers: Ter, Onyar, Galligants, and Güell. The city was studied considering its division in 62 city sectors at macro-scale and 997 allotments at micro-scale.

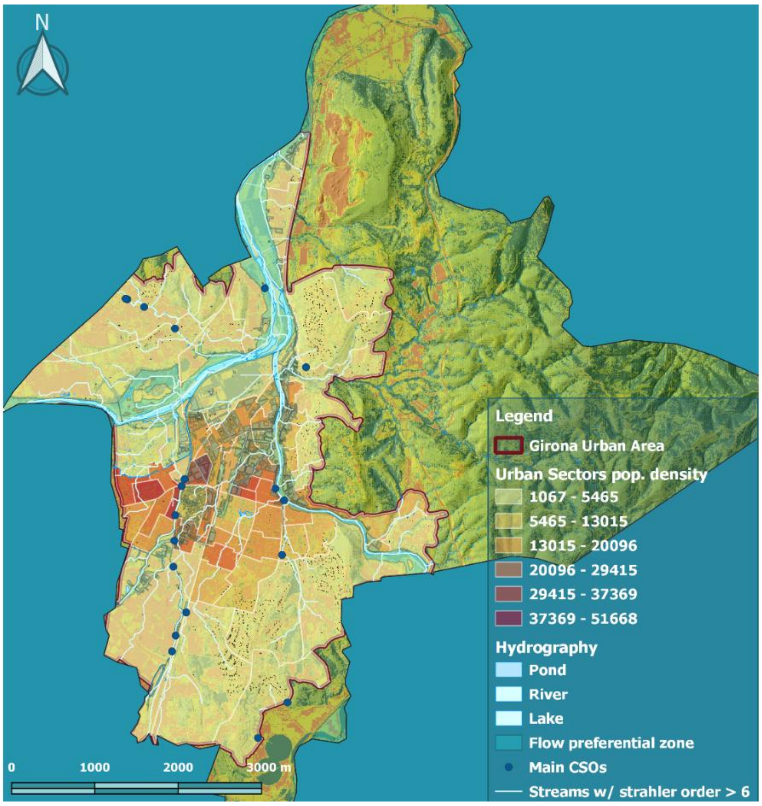

Figure 2. Study location with the representation of sectors and context variables influencing the siting of sustainable water management solutions across the urban fabric
Source: Original data from the research based on datasets from different open-source data

Results and discussion

The criteria were ranked proportionally to their importance (ranking position). Typically, ranking is determined through expert consultation or public input. However, in this study, rankings were derived from a bibliographic synthesis of 51 peer-reviewed articles that examined interlinkages between context variables and the scale of circular and green interventions on urban water systems. This ensured prioritization grounded in scientific evidence (Eggimann et al., 2016; McFarland et al., 2019; Stessens et al., 2017). This method captures well-established relationships—such as the benefits of economies of scale in dense areas or the need to prioritize flood-prone zones—and enables a systematic, evidence-based approach despite the absence of stakeholder weighting. As this study is academic and tests the methodology, bibliographic weights were appropriate; for real-world use, participatory weighting is recommended.

The 25 criteria used span multiple domains, including socio-demographic variables (e.g., population density, educational attainment, elderly population share, income inequality), environmental factors and hazards (e.g., elevation, slope, impervious surface coverage, surface temperature, groundwater depth, accessibility to green space, presence of natural drainage paths or flood-prone zones), infrastructure-related indicators (e.g., combined sewer overflow occurrence, identified problem areas by utility services, distance to the wastewater treatment plant), and proxies for reuse and greening opportunities (e.g., number of institutional buildings with high water reuse potential, irrigation needs indicated by area of green spaces, proximity to local food markets).

After running the GIS-MCDA model in R, priority sites were identified at both sector and allotment scales for circularity and greening. Subsequently, an arithmetic spatial priority index (weighted sum of normalized scores) was calculated, combining the scores for both greening and circularity (Figure 2). Four decision matrices were generated—one for each purpose (circularity and greening) at each spatial scale (sectors and allotments). Circularity-focused matrices prioritized the recovery of wastewater and stormwater for water reuse, energy generation, or nutrient recovery—supporting the water-energy-food (WEF) nexus. In contrast, greening-focused matrices emphasized Water Cycle Restoration (WCR), ecosystem services, and food production, aligning with the water-ecosystem-food nexus.

The methodology successfully ranked both qualitative (e.g., land use type) and quantitative (hydrosocial) criteria to identify priority locations across spatial scales. Results showed that greening was prioritized in industrial zones and dense, impervious areas, while reuse interventions—including stormwater harvesting—were favoured in high-elevation areas distant from centralized plants. These outcomes align with established planning knowledge: underserved industrial zones benefit from increased green space, while decentralized reuse in elevated zones reduces pumping energy and infrastructure costs (see Step ii for criteria selection based on elevation and distance). By confirming expected patterns and uncovering new opportunities, the model offers planners a data-driven tool to prioritize areas with potential for synergistic circular and greening benefits. For example, the identification of high-elevation sectors far from the treatment plant as prime candidates for water reuse reflects the PDSS's capacity to support strategic, early-stage decision-making without reliance on detailed hydraulic simulations.

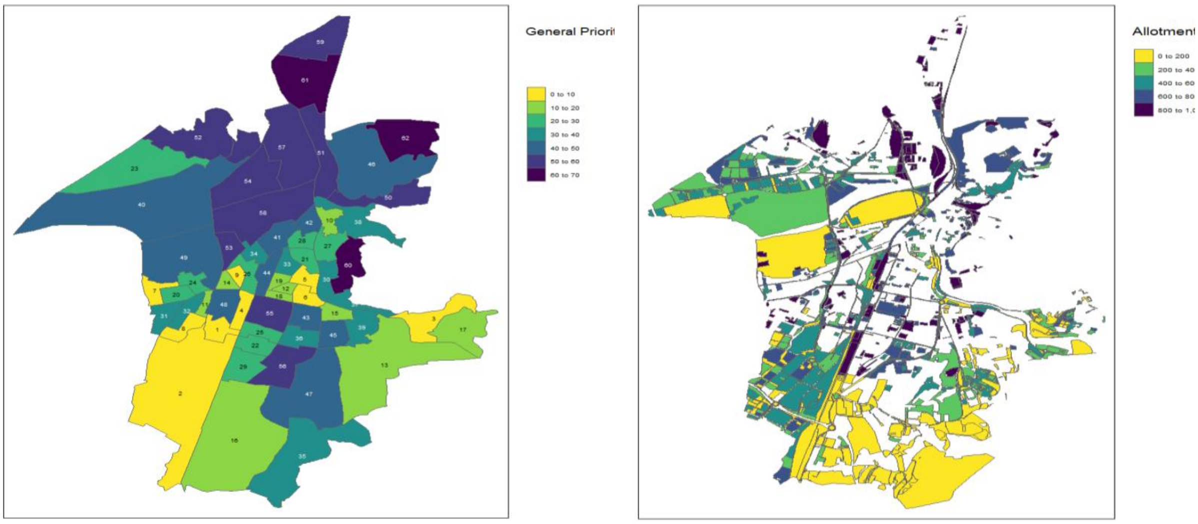

Figure 2. Ranking of the city sections considering the arithmetic priority value of the combined scores for greening and circularity purposes and priorities for the allotment scale.
Source: original data from research

Conclusions and future work

This PDSS offers a structured and scalable approach for cities transitioning to circular and green UWSs. The Girona case confirms that a GIS-MCDA screening can reveal priority areas where simultaneous circularity gains and green-space deficits align, offering data-driven insights that complement planners' local knowledge. Ongoing research focuses on developing scenarios representing different transitional states of urban water systems, with varying population and area coverage served by scaled circular and green WMUs. This includes finalizing the technology catalogue to incorporate diverse, multipurpose technologies for water reuse, nutrient recovery, and food production. The impact of these scenarios will be assessed using key technology metrics and quantification strategies, employing open-source tools and methodologies inspired by Pueyo-Ros et al. (2024), to ensure robust analysis. The current approach relies on general performance metrics, prioritizing solutions with high Technology Readiness Levels.

Additionally, the tool is designed with flexibility in mind: users can adjust the criteria and their weights based on local priorities and data availability, which is crucial for applying the PDSS in data-scarce environments, and allows proxy-data substitution (e.g., Open Street Maps layers, Sentinel-2 imperviousness, NVDI) where local layers are missing. A key feature of the PDSS—though not implemented in this academic application—is its capacity to incorporate stakeholder and community input (e.g., through participatory weighting of criteria during workshops). Criteria weighting enhance transparency and ensure the model's priorities reflect local values and expertise. Finally, future work will include detailed scenario development and city-wide mapping of suitable circular water schemes.

While future integration with graph theory (Calle et al., 2023) and hydraulic-hydrological modelling (Rauch et al., 2017; Sitzenfrei & Rauch, 2014) could enhance the network design optimization and assess infrastructure impacts, these aspects fall beyond the present research scope. Excluding them ensures a simpler, more practical and tangible planning process to be used by decision makers. This approach also enables the construction of a modular, on-demand PDSS, capable of providing different features based on user needs. Our focus remains on leveraging MCDA to guide the siting of solutions and scenario development, aligning with urban sustainability and resilience objectives.

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