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Review

How Scale Influences the Resilience of Urban Water Systems: A Literature Review of Trade-Offs and Recommendations

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Abstract: Climate change severely affects urban water systems (UWSs). Infrastructure historically designed for milder conditions cannot manage growing water demands and extreme events. To obtain a resilient water sector, adaptation and mitigation strategies must address rising water challenges while striving for net-zero emissions. Researchers have noted that extreme decentralization is positively associated with closing cycles while reducing transport costs. However, part of the scientific community defends centralized schemes due to economies of scale. The objective of this systematic review is to understand the trade-offs associated with the adoption of different scales at UWSs design and how this impacts system resilience. This process includes identifying different scale trade-offs and unique environmental aspects that influence the optimal scale suitability. A clear distinction was made in terms of scale concept and classification, considering different design levels. That is, considering the UWS at the city level and water management units (WMUs) at the local level. Similarly, a classification of different scales for each level, covering all water streams—supply, wastewater, and stormwater—was introduced. We defined the key environmental aspects that influence the optimal scale and location suitability: ten at the city-catchment level and eleven at the site-neighbourhood level. Scale impacts three major UWSs functionalities that have repercussions on urban resilience: net energy, net water, and ecosystem services (ES).

Keywords: urban water systems; resilience; planning; scale; suitability; urban water management; water-energy nexus

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1. Introduction

Urban areas can be considered metabolizing organisms; they import flows from other ecosystems and (re)circulate them among users, while part of it leaves city boundaries as multiple forms of waste [1,2]. Cities account for 78% of all carbon emissions and 60% of residential water use [3]. This usage is impacted by changes in climatic conditions. For example, water scarcity affects approximately 11% of the EU population and, by 2030, will likely affect half of Europe's river basins [4].

The provision of water to cities, the subsequent wastewater treatment, and storm management require three main subsystems within the UWS: the water supply system (WSS), the wastewater system (WWS), and the urban drainage subsystem (UDS). These subsystems interact with each other and with the hydrological natural subsystems (Figure 1) to form the urban water cycle (UWC) [5–9]. For instance, the UDS is affected by the atmosphere via evapotranspiration and rain; soil and underground water sources can influence water supply; and infiltration processes can reduce stormwater flow to pipes. Usually, the UWC includes external water inputs from larger river basin resources. In coastal cities, it may also interact with marine water bodies, through outfalls and desalination plants [10–12]. They include networks, treatment plants, green infrastructure, and hybrid green-grey solutions, which are organized as centralized or decentralized water management units (WMUs), offering options for circular loops [13,14]. The spatial scope of this review is the UWS.

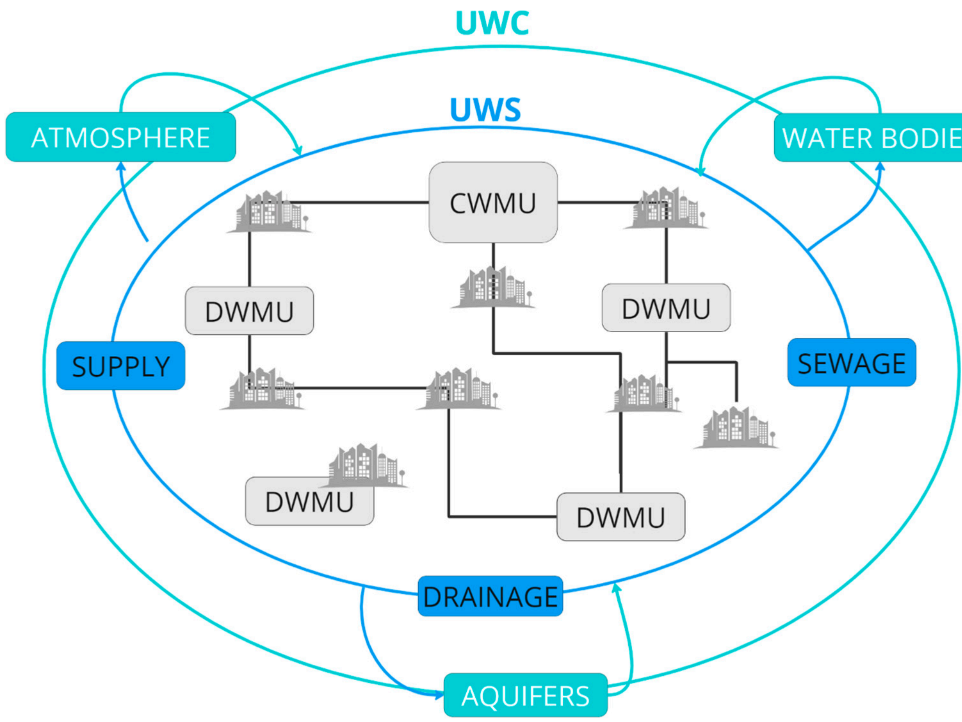

Figure 1. Urban water system (UWS) within the urban water cycle (UWC). Acronyms: DWMU: decentralized water management units; CWMU: centralized water management units.

In general, UWS resilience refers to the system's ability to anticipate variability, absorb disturbances and reduce damage, adapt to changing conditions, maintain functionality within a certain range over long periods, and recover back to acceptable functioning levels after disruptions, ensuring services now and in the future, while nature is still protected [15–17]. Analogous to the UWC, which can present multiple dimensions [7], resilience is multifaceted and has been referred to as having a wide variety of economic, social, organizational, environmental, and technical dimensions [18].

In this study, drawing on seminal work on resilience [15,17,19], we consider that three capacities can describe the resilience of UWS: **(i)** Absorptive, which involves absorbing and minimizing the consequences; **(ii)** Adaptative, which refers to the ability to adapt to changing operational conditions and recover quickly from stress while maintaining a minimum level of functionality. **(iii)** Restorative: rapidity of the system's return to an acceptable level of serviceability. It involves repair, replacement, or other recovery efforts. Common parameters used to measure the resilience of UWSs include water storage, water quality for safe use, flood, overflow, and runoff volume, baseline water stress (the total withdrawals related to the available renewable water supply), the return flow ratio, the drought index, the flood index, the city heat island index [5], network redundancy, the inflow-demand reliability indicator, and system energy surplus [17]. When assessing resilience, it is important to consider the various functions of a system and the trade-offs that exist between them. This systemic approach can effectively enhance the overall resilience of UWSs [17].

Thus, a full understanding of scale interactions and trade-offs can help optimize UWS design to enhance resilience properties. The definition of suitability recommendations for different scales can be translated into actions tailored to local water needs and demands [20].

Scale issues substantially impact how UWSs are designed and implemented, and a detailed understanding of these issues requires analyses that take a whole-of-system approach [21].

The objective of this literature review is to synthesize information for promoting best planning practices in the arrangement of UWSs, particularly in the context of how different scale scenarios impact UWS resilience. Scale is a theme discussed by researchers, but these discussions usually limit themselves to only one approach (decentralization vs. centralization), and their analyses often consider only one of the three subsystems (WSS, WWS, and UDS); thus, potential trade-offs and synergies across these sectors are missed.

There is a need to go beyond extremes and study how the optimal scale varies among WMUs and UWSs. How does the scale of each WMU impact the final scheme of the UWS? There are many trade-offs when transitioning from small to large scales. Usually, to gain a benefit, other aspects of the UWS are negatively impacted. How does this dynamic function? How is scale affected by urban conditions? Which scale is more appropriate under certain conditions? Is it possible to simplify the problem by grouping environmental conditions into two hierarchical analysis levels? How is scale related to UWS resilience, and what are the main impact routes of scale on increasing urban resilience?

The authors considered variables related to the suitability of different environments in the context of defining different scales at each WMU and at UWSs; they also accounted for the possible impacts of scale intertwined with other metabolic flows within the water–energy–food and ecosystem (WEFE) nexus. The key objective was to develop a greater level of understanding focused on scale trade-offs, especially across the water-energy nexus, considering the three subsystems within UWSs. Then, the feasibility of different scales of the WMU and the overall schemes of the UWS at both the city and site levels were studied to determine the optimal scale.

The optimal scale definition is proposed to be a function of a two-level hierarchical analysis:

1. The scale of the UWS is defined as a function of the environmental catchment and city-level variables and thus varies according to city typologies.
2. The scale of the WMU, considering neighbourhood and site conditions, varies across the urban fabric according to hydro-social variables.

A better comprehension of the relationships between different scales and environmental urban conditions can help decision-makers enhance the UWS scheme and increase the services of WMUs, especially under climate-stress conditions. Moreover, identifying clearer routes through which scale impacts urban resilience is important when determining which performance metrics should be considered when planning and operating UWSs.

The findings and contributions of this review relate to the proposal of a comprehensive scale conceptualization, establishing a clear distinction between scale classifications for UWSs and WMUs, and incorporating a nomenclature that covers all three subsystems (WSS, WWS, UDS). Additionally, scale trade-offs were listed, specifying the UWS resilience properties and affected subsystem(s). Finally, the environmental aspects influencing optimal scale and location suitability were defined at the city-catchment (CC) and site-neighbourhood (SN) levels.

2. Materials and Methods

The literature related to urban water cycle technologies was retrieved from the Web of Science (WOS) database and considered English articles worldwide. A total of 6225 published articles were obtained for all years (keywords used are shown in Appendix A). The screening process was conducted at two levels: the title and abstract and the full-text level. The preliminary criterion used was article classification according to the number of citations. Different citation number thresholds were set according to the publication period. Furthermore, articles from funding projects related to the review scope were included when the number of citations was greater than 25. Complementary articles related to the theme were retrieved through the machine learning web tool "connected papers" (Figure A1, in Appendix A), which enabled the collection of highly cited papers related to the articles found through the keyword screening from WOS. Finally, reports and national and international guidelines on the review subject were also considered. The screening process involved reviewing titles and abstracts, followed by selecting articles specifically addressing the scale of UWSs. This process resulted in 51 scientific articles and 6 grey documents, which were further examined. Overall, a total of 57 articles, reports, and norms were thoroughly reviewed (Figure 2).

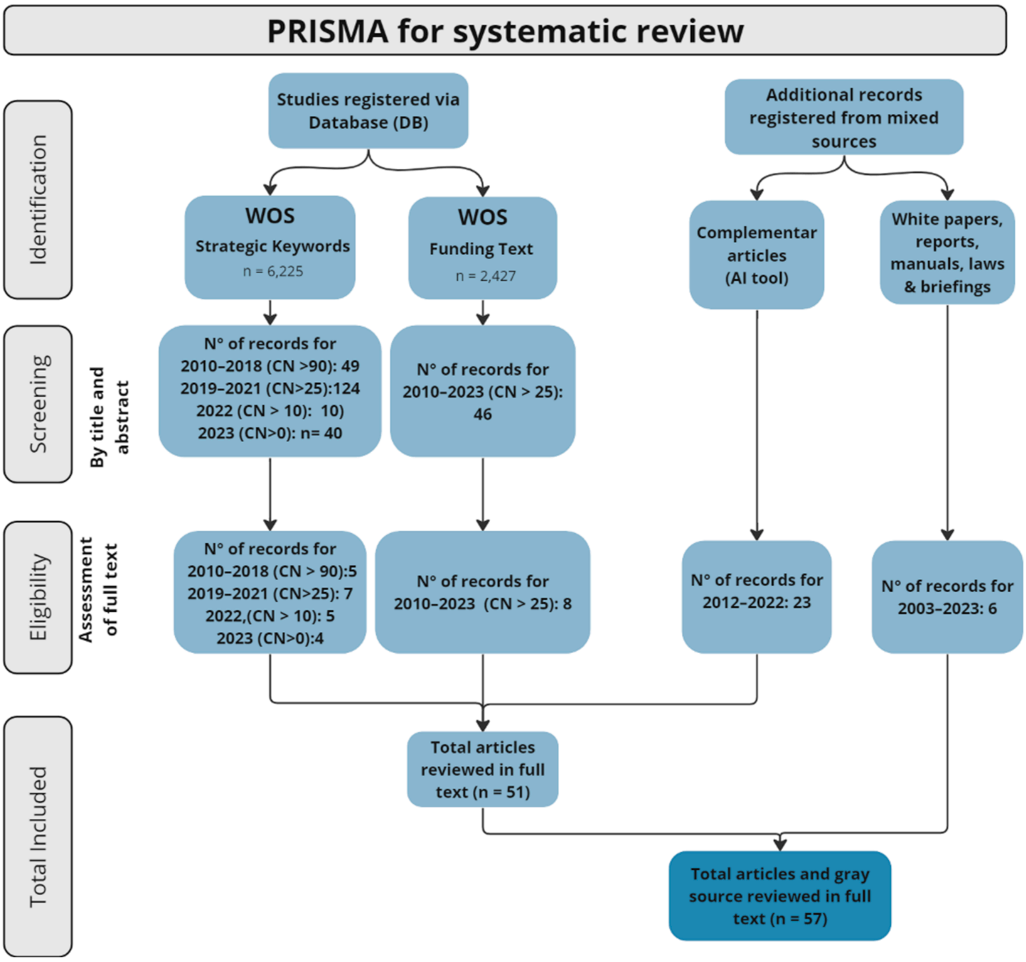

Figure 2. Methodology for the review following the PRISMA concept.

The selection of strategic keywords was guided by the study's goals and the similarity between key terms, resulting in seven keyword groups. These groups encompassed various aspects: the study context, including variations in terminology used in cities; the resources under investigation, such as different water streams and their word variations; frameworks related to UWS design and scale selection, such as decentralization and Integrated Water Management; technological approaches associated with UWSs scale; keywords related to the research approach, valuable for characterizing the technologies encompassed by UWSs design; keywords referring to assessment methods, such as systematic reviews, life cycle analysis, and suitability assessments; and keywords related to general interests addressing the social perspective of scale design implications on UWSs resilience, beyond technocratic considerations. Another keyword group, related to research projects that address studies about UWS design, was also retrieved. All the keywords used are shown in Appendix A.

3. Results

From the total of 57 articles and grey documents, 35 discussed sewage, 30 discussed supply, and 20 discussed urban drainage.

3.1. UWS Scale Definition

Scale definition depends on the concepts of centralization and decentralization. The literature has not made a clear distinction between the scale concept at the system or unit level (Figure 3). The UWS scale refers to the magnitude of water flowing through the system managed by centralized or decentralized WMUs, which are the elements that compose this system. The UWS can rely entirely on centralized treatment plants for all types of water streams (supply, wastewater, or stormwater) or can present distributed WMUs covering a diverse range of scales [22–28].

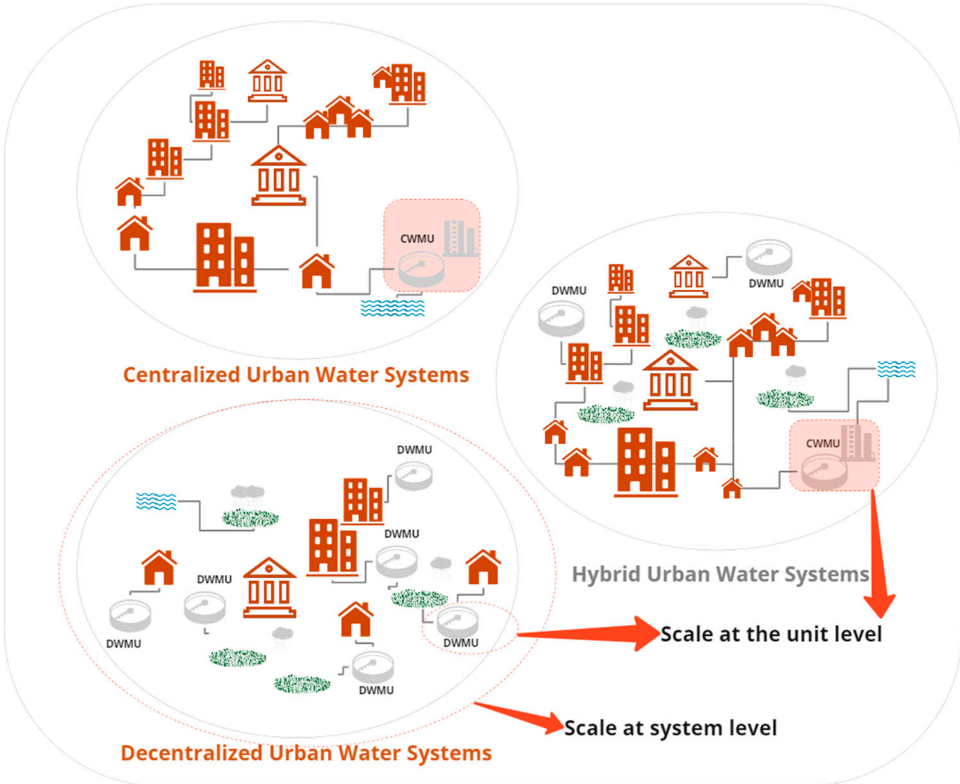

Figure 3. Urban water systems scale conceptualization.

Centralized urban water systems (CUWSs) consist of large treatment plants, distribution networks, collection pipelines, and drainage infrastructure carrying water far from the point of origin [22]. CUWSs usually assume a linear design, from freshwater abstraction to wastewater and stormwater discharge on water courses. Centralized WMUs include large treatment plants and storage water tanks in the supply subsystem to guarantee flow continuity at adequate pressure for water users [23]. Additionally, drainage systems (frequently combined with sewage) can rely on underground tanks to accumulate water during wet weather [24]. This design can prevent floods and overflows to water courses, as well as operational flow disturbances that affect treatment performance in wastewater treatment plants [25–30].

In the past years, the planning and design of decentralized systems have gained traction within the concepts of Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) [21,22]. Both concepts focus on the coordinated management of water supply, wastewater, stormwater, and urban planning. They utilize locally available water sources such as rainwater tanks, stormwater harvesting, greywater reuse, and recycled water. According to those management paradigms, DWMUs are mostly emphasized in the literature when associated with technologies designed for water reuse [12,21,22,25,31–38]. As a result, schemes are better capable of diversifying water sources through closed loops centred on nonpotable reuse (NPR) [21,22,39]. Decentralization is also associated with distributed facilities and spaces that mimic nature to manage stormwater through green infrastructure (GI) [13,27,28,40]. GI is referred to in this document as any nature-based solution (NBS), green-(blue), or hybrid green and grey asset [41] of the system that mimics nature and contributes to the water cycle restauration. A decentralized UWS consists of overlapping small- and medium-sized facilities for water storage, distribution, and collection that occur at multiple spatial scales and can duplicate water pathways for potable and nonpotable water. As a result, decentralization enhances fit-for-purpose reuse of nonconventional water sources [31]. Decentralization places a strong emphasis on environmental functions, such as water reuse and reduced bulk water transfer, allowing for a wide range of technological options to be customized based on the intended purpose [22].

If decentralized, UWSs are composed of distributed WMUs working independently from each other. However, in urban environments, WMUs are ideally integrated into the centralized network, thus complementing the existing system rather than requiring a total system overhaul. This configuration involves service backup in case of failure and is referred to as a hybrid urban water system (HUWS) [22,39,42]. WMUs within a HUWS can be organized into larger managed cluster areas [39]. The clusters are managed at hierarchical network levels. The proposed HUWS combines decentralized onsite and middle-scale distributed treatment and reuse facilities to supply both potable and nonpotable water for various purposes (commercial, residential, green spaces, and industrial) and to manage stormwater through WSUD [21,27]. In summary, HUWS constitute a synergetic combination of centralized and decentralized WMUs, based on the circularity principle for water, designed to provide cascading, reuse, and recycling of multiple locally available water sources (rainwater tanks, stormwater harvesting, greywater reuse, and recycled water), to create new patterns of interaction and complexity and realize the value of water [31,39,41].

3.2. Scale Classification

The scale classification at system and unit levels varies among authors, and the literature does not clearly distinguish between the two. The classification also assumes different nomenclature for each subsystem within the UWS—supply, wastewater, and drainage. Considering the whole UWS, the literature terminology usually classifies systems as centralized, decentralized, or a combination of both, constituting hybrid systems [8,21,36,39,43]. A novel nomenclature classification distinguished UWSs as nongrid, small-grid, hybrid, or grid-dominated systems [44]. Nongrids include systems without pipes between individual buildings. Small grid systems present pipes between a small number of individual buildings. Grids are constituent elements of today's centralized systems. Hybrid systems integrate nongrid and small-grid solutions into grid-dominated systems. The interesting aspect of this classification is that it allows us to categorize UWSs considering the scale of the WMUs and the degree of interconnectedness through the network (grids).

WMUs within the UWS have been previously classified based on the number of people served or drainage area and range from centralized to intermediate levels of decentralization (urban cluster facilities) to complete decentralized facilities (onsite or individual solutions). Water supply and wastewater subsystems are often classified similarly; for example, the scale classification proposed by [45] states that units are decentralized at the household scale (<379 m^3/day flow rate), semi-centralized at the community scale (379–19,000 m^3/day) and centralized for plants at the city scale (3800 to 57,000 m^3/day or larger). In another study [46], the following classification was proposed: small-scale classification for onsite units serving up to 40 persons; medium-scale satellite sand urban cluster units (population ranging from 20 to 47,000), and large-scale classification for centralized city-scale units (serving populations of 9090 or greater). Additionally, the classification proposed by [22] introduces three different scales for decentralized water and wastewater units: an onsite scale for individual properties; a cluster or development scale serving two or more dwellings, for which a local water supply, sewage collection and treatment are operated using a common ownership model; and a distributed system scale that provides services for large developments of 100 properties or more and is operated by water utilities.

For the drainage subsystems, the scale classification of WMUs was performed in the realm of sustainable urban drainage. A review by [47] revealed that the term "source control" can include three categories: urban best management practices (BMPs), which are housekeeping practices used to avoid pollutants coming in contact with runoff; site control units, which are used for areas of less than 2/3 hectares; and structural area or regional controls (which are often end-of-pipe solutions), which are appropriate for areas above ¾ hectares. First flush control drainage measures [48] were also classified according to the control implementation stage into source control, process control, and terminal treatment. NBSs have also been classified on different spatial scales. For example, ref. [49] grouped them into micro/neighbourhood or building scales, meso/district scales, and macro/city scales, while [50] categorized them into urban regions, cities/metropolises, neighbourhoods and building blocks.

3.3. Scale Trade-Offs

Centralization and decentralization present advantages, disadvantages, and trade-offs (Table 1), reflected in system functionalities (energy surplus, water storage, sustainable drainage capability, governance, and many more), which, conversely, influence the backbone components of the three main resilience capacities (absorption, adaptation, and restoration). The literature has cited many components of resilience capacities, of which four are considered key for UWSs: **(i)** Reliability, which consistently meets the goal; **(ii)** Robustness, which is the ability of the system to address a broad variety of contaminants and resist catastrophic failures; **(iii)** Redundancy (flexibility, connectivity), which is the ability to satisfy operational obligations using alternative components and strategies beyond minimum requirements to ensure that treatment goals are more reliable; **(iv)** Learning and investment ability, which relates to the degree of society cohesion, governance alignment, and investment capability to be able to change and retrofit to more sustainable paradigms while avoiding anthropic disruptions [15,17,19,51]. Therefore, an analysis of the impact of scale on UWS resilience was performed by evaluating the interactions between the scale trade-offs and the components of resilience capacities (resilience properties). This trade-off ultimately affects system functionality.

Table 1. Scale trade-offs impacting UWS resilience in different subsystems.

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Water storage (Diversification of water portfolio with climate-independent water-sources)	Reliability, Redundancy	Fit-for-purpose supply is more convenient at small-scale systems due to the proximity to the point of reuse. For example, nonpotable reuse to irrigate green DWMUs. On the other hand, the larger it is the scale, the greater the flow stability, allowing more security of the demand concerning reclaimed water generation [21,22,25,27,31,39]	WSS WWS UDS
Water Storage (Diversification of water portfolio)/Energy surplus/Governance	Reliability	Increasing the number of decentralized circular facilities increases the buffer capacity against scarcity and vulnerability. On the other hand, water reclamation and monitoring at these facilities will demand additional energy, with lower economies of scale for treatment than at larger units [21,31,44,52,53].	WSS WWS UDS
Water Storage (WMUs interconnections)	Reliability, Redundancy	Decentralized schemes intertwined with each other at the cluster/district level, or the whole system intertwined through smart water grids differ from extreme decentralized schemes composed of autonomous DWMUs. The higher the interconnectivity, the higher the flexibility (redundancy of those systems). On the other hand, risks of cascading effects or cyber-attacks that can reach a greater number of facilities is increased [51,54].	WSS WWS UDS

Table 1. *Cont.*

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Energy surplus	Reliability	Smaller-scale units generally reduce energy requirements for distribution, collection, and conveyance, while larger treatment facilities present, per volume, a lower carbon footprint, energy demand and cost for treatment, due to economies of scale [31,36,42,46].	WSS WWS UDS
Target water demand	Redundancy	Circular distributed smaller-scale units hold the ability to mitigate peak water demand and, thus, reduce the need for capital investments to increase the treatment capacity of existing supply facilities, while relieving pressure on central treatment plants and reducing wastewater pumping costs. On the other hand, each unit holds a smaller storage capability, being easily affected by external disturbances (more failures per time) [31,33,42,51,55].	WSS WWS UDS
Governance (Operation and monitoring)	Reliability, Redundancy	Larger-scale systems suppose less complexity to monitoring than operating multiple smaller units. This arises from fewer points to control in a larger-scale system. On the other hand, if anomalies are detected, is necessary a greater effort to recover, since the potential damage affects higher volumes rapidly; additionally, if one CWMU fails, the potential disruption damage (service covered area and people reached) is higher [32,39,52,56].	WSS WWS UDS
Governance (river basin discharge control), Sustainable Drainage a	Reliability	Large scale water collection and treatment sites alter natural hydrological systems leading to stream depletion, shoreline erosion, contamination, and other negative biological outcomes. On the other hand, high discharge flows in arid river basins are frequently responsible for maintaining minimal ecological flows and water quantity for unplanned reuse by downstream systems [12,31].	WSS WWS UDS
Water Storage (water cycle restoration), Sustainable drainage	Redundance, Robustness	Smaller-scale green-DWMUs facilitate local management and reduce the volumes of rainfall converted into runoff, avoiding piping overflow while protecting headwaters. On the other hand, they present a lower return period design capability, being unable to store a great amount of rain. Especially during extreme rainfall events, flow efficiency management is reduced. Thus, larger-scale facilities are needed for managing stormwater when dealing with high return periods [24,40,48,57].	WSS WWS UDS
Water storage (Leakage loss reduction through conveyance systems)	Reliability, Learning and investment capability	Systems based on a higher decentralization degree have lower water loss, due to leakages in water supply distribution, and soil contamination, by occasional exfiltration. On the other hand, monitoring demand-side management (DSM) is more complex. DSM hopes to evaluate human behaviour, detect water losses, and reduce consumption patterns based on data-driven measures. As some of the supply comes from different sources (ex: households' water micro-trading), other than from the central utility plant, this task will become more challenging [43,54].	WSS WWS UDS
Sustainable drainage, Governance	Redundancy, Learning and investment capability	Sustainable drainage is based on distributed small scale GI management units. They can deliver ecosystem services across the city. On the other hand, the footprint is higher than when employing grey infrastructure; and maintenance requirements are usually more complex since their backbone is a living ecosystem body [25,58].	WSS WWS UDS
Energy surplus Water quality	Reliability, Redundance	Large UWSs with CWMUs, obligated to remove phosphorus from wastewater, demand higher energy requirements due to longer aeration period; this prompts stream separation at the source; source separation could employ hybrid schemes designed to harvest energy/nutrients from black water at DWMUs, while lower carbon concentrations flows are treated at CWMUs. On the other hand, conventional centralized facilities hold higher operational security, lower complexity of phosphorus removal, and lower water quality problems due to malfunctioning risks [59,60].	WWS WWS UDS
Water quality	Robustness, Reliability	HUWS encompasses the integration of DWMUs and CWMUs. The centralized network functions as a background multi-barrier system for wastewater and/or stormwater. On the other hand, interactions of centralized and decentralized units, like increasing solids and other contaminants concentration in the wastewater pipes could increase corrosion and sedimentation problems [8,21]	WWS WWS UDS

Table 1. *Cont.*

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Governance	Learning and investment capability	Decentralization lowers capital intensity and shortens the construction timeline, through modular implementation. This avoids unutilized infrastructure in the beginning years or the risks of assuming population projections that may not reach the expected size. Moreover, decentralized schemes hold greater reconfiguration and retrofitting capability than centralized ones. On the other hand, the frequency of investment cycles will increase, requiring more retrofitting for additional units [8,31,61].	WWS WWS UDS
Governance	Reliability, learning and investment capability	Management of smaller-scale facilities favours the cohesion and synergies between local actors. On the other hand, larger WMUs count with a supportive legal framework and a greater acceptance by the water sector, with a deep understanding of operation and maintenance procedures. Thus, avoiding possible disturbances of changing the management paradigm. Complementary, society engagement demands greater effort from institutional parties to put in agreement multiple actors, which must receive adequate training and maintain continuous commitment during long periods [12,25,32,39,46,56,59,62].	WSS WWS UDS
Water justice	Redundancy, Learning and investment capability	Decentralized water units can augment resources and provide deeper, long-term cost savings to residents in underserved neighbourhoods by replacing or fixing water infrastructure closer to its source, showing an inherent ability to improve water service equity and greater adaptability to local contexts. On the other hand, facilities maintenance can be forgotten by authorities, and not get the adequate investment or structure because low-income communities usually provide no profits [31].	WSS WWS UDS
Governance (operational and monitoring capability)	Redundancy, Reliability Learning and investment capability	Smaller-scale units favour effluent separation at the source, improving nutrients and energy recovery. On the other hand, operational costs, and complexity to recover are higher. There is a greater experience of resource recovery practices at larger-scale units. Centralization also favours an increase in the total load to recover, even though materials are more diluted [31,32,36,46,59].	WSS WWS UDS
Energy harvesting	Availability of Energy surplus	Harvesting thermal energy for hot water energy savings is more advantageous when closer to the source, at smaller WMUs, due to higher efficiencies and reduced heat losses to the environment during conveyance. On the other hand, the total energy load to be harvested is lower than in larger systems with higher flows; and flows must exceed a minimal threshold to achieve economic availability [38,46].	WSS, WWS UDS

Notes: * Grey intensity in the table: White represents no impact; Lighter grey represents lower impact intensity in the subsystem; Darker grey indicates a greater impact intensity in the subsystem.

Decentralized systems present a greater ability to utilize a diversified portfolio of water sources and increase system buffer capacities through the NPR closer to the source and user. Therefore, it reduces potable water demands [22,31,36,37,39,42,55]. According to [31], water savings promoted by closed-loop decentralized systems reduce the energy demand and ecological footprint of UWSs. For example, past studies of onsite greywater or combined greywater and rainwater treatment have achieved system-level energy savings of more than 50% and reduced consumption by 75% compared to conventional systems. Decentralized solutions are frequently composed of green-blue or grey-green solutions, especially when the enhancement of urban land water management capacity through WSUD is considered [21,27,62]. NBSs can be a beneficial addition to decentralized water systems, acting as a prefiltration step for drinking water treatment, a polishing step for wastewater treatment, or a comprehensive runoff treatment zone for water before its re-entry into the watershed [14,58]. Nevertheless, the potential for adequate retention of stormwater is greater at small scales [40], although, during extreme events, their ability to manage flows decreases due to adverse hydrogeological conditions, such as fast saturation of the first soil layers [24,40,48,57]. By extracting and reclaiming wastewater from upgradient locations, decentralized treatment can minimize the need to pump reclaimed water back to users [55]. This could be accomplished through DWMU based on sewer mining techniques [63] to serve downstream areas. Decentralized water technologies can secure preferable business conditions for urban industries, alleviate disproportionate access to urban water services, increase the energy efficiency of compact and mixed-use developments, and address local issues through community involvement [31]. Linking the potential of decentralized water infrastructures with the broader urban development agenda can both attract more financial resources and create opportunities for intersectoral collaboration [31]. Considering spatial characteristics, under the scope of global analysis, particularly in developing countries without old and established water conveyance systems, decentralized water treatment and distribution allows flexibility in addressing water access and sanitation in a modular treatment network [39,44,58,59]. Modularity can flex with the expanse or sparsity of a dynamic population, improving redundancy through smart-water grids [39,54]. Distributed plants may also be more resilient to wilful attacks, as they limit the impacts of system failures to smaller areas [31,42]. Conversely, the risks of cascading effects and cyber-attacks increase at higher levels of network interconnectedness between distributed WMUs [51,54]. In the case of malfunction, decentralized systems, particularly residential ones, pose challenges as technicians may take longer to address issues. These systems require efficient instrumentation for automating their operations and for triggering alarms in central water-control units based on high-tech solutions [39,43,53,54]. The flexibility of decentralized systems presents trade-offs, especially concerning the greater sensitivity to variable flows throughout the water system and the increased management complexity. Subsequently, they can be seen as less reliable [31,58]. The latter is one of the reasons for selecting WMUs at the cluster scale [39,46,52,55].

Centralized WMUs offer greater service reliability for water reuse than do smaller-scale WMUs when considering consistent and continuous flow rates and improved water quality monitoring. Monitoring water quality is simpler at centralized systems due to fewer sampling points and the presence of instrumentation and skilled personnel right next to the WMU, thus reducing costs and operational complexity [43,52]. These systems benefit from specialized teams and companies with appropriate management experience. Due to the added capital and operational costs associated with high network complexity requirements, centralized configurations discourage fit-for-purpose water supplies and favour quick residual and rainfall water removal to central treatment plants. Frequently, the operating costs for collection/distribution networks in centralized reuse systems counterbalance economies of scale in treatment [42,46,55]. For example, water reuse in centralized systems would require more pumping energy because facilities at these schemes are typically located at low points in collection systems. In water-stressed regions such as California and San Diego, the conveyance energy can be 20 to 39.5 times greater. In the US, 80% of electricity in the water sector is used for conveyance [42].

Within the WEFE nexus, scale affects the capacity for nutrient recovery. The closer the material is to the source, the greater its concentration [46]. Treatment proximity to the source also influences the amount of energy required to extract and recover materials from wastewater [49]. Thus, mixing resources should be avoided during the recovery stage of WMUs. For example, there is a reduction in losses to the atmosphere during pipe transport and storage, which can account for 50% of the potential nitrogen that needs to be recovered [49]. The treatment of urine from NoMix toilets has shown higher recovery rates [46,49]. Decentralized scenarios also require smaller investments in piping infrastructure for stream separation and would be easier to implement for new buildings and development areas [31,36]. With all that in mind, it is reasonable to assume that nutrient concentrations can be even lower under wet conditions; consequently, recovery would demand more effort due to dilution and added contamination from runoff and carried materials. The trade-off is that additional local infrastructure is needed since more energy and operational complexity are required to separate and recover materials. Furthermore, the total load of resources to recover, even though they are more diluted, increases at larger scales [46,49,60,64]. Thus, the optimal scale is defined based on the specific context of the location and the selected technology [46,49].

Recent studies and reports support the adoption of middle-scale DWMUs at HUWS. Hybrid systems can exploit multiple-scale approaches, in which decentralized units return residuals to centralized treatment systems downstream for further treatment [36,39,41,46]. Hybrid systems, with coexisting centralized and decentralized treatment plants, handle freshwater, water reclamation, and resource recovery; furthermore, they receive concentrated fractions of wastewater and biosolids from smaller treatment facilities for further reclamation [21,22] or vice versa [59]. This approach exploits the decentralized approach, reducing supply expenses to treat water to potable standards for nonpotable uses, the transport distances, and associated energy costs [39], while benefiting from economies of scale at the middle scale and larger units [36]. The existing infrastructure is maintained to guarantee high-quality standards and adequate monitoring for potable supply. HUWS also allows for profit from the existing infrastructure and avoids future retrofitting at pipelines or centralized units due to increasing water flow. While integrating DWMUs into the current centralized system offers numerous benefits, the interactions between CWMUs and DWMUs present complexities that could cause unintended long-term negative consequences [21]. For example, reduced flows and increased solids concentration in wastewater pipelines could escalate corrosion and sedimentation issues [21,31]. Retrofitting UWSs for the transition to hybrid schemes is challenging due to limitations such as potential high costs and scarce availability of land, different investment cycles compared to centralized solutions, and governance barriers [8,61,65]. Managing the increased complexity will require a new approach at smaller-scale units, potentially involving private actors, and the creation of new responsibility roles to ensure water quality and safety [8].

3.4. Scheme Suitability

What is the optimal scale of water schemes for the UWS and WMUs? This seems to be a straightforward question. However, the answer depends on many factors, ranging from the actual state of the UWS [42,52,59] to the surrounding environmental conditions [8,21,36,38,61] including managers' and society's values, which influence the selection of the most adequate option [66,67] according to the priorities established by behaviour trends. The analysis of environmental conditions can be performed at two hierarchical levels. First, variables at the catchment-city level must be considered. This level embraces the characteristics of the river basin and city location within the basin, which, combined, generate many city typologies, namely, city hydrological typologies, since the aim is to improve UWS design based on strategies that consider cities' hydrological categories. Similarly, the second level of analysis refers to understanding how site and neighbourhood characteristics vary across the urban fabric. The comprehension of a city typology helps identify factors that influence macro aspects of the UWSs. For example, the main water sources and characteristics of the CWMU and the total flow amount should be preferably treated by decentralized and centralized facilities. Moreover, site characteristics are fundamental for defining each unit's optimal scale and selecting priority sites that are most appropriate for DWMUs. Thus, this review aimed to identify not only the relationships between those conditions at both levels, but also the most suitable schemes for UWSs at the macro level and the best scale approach for WMUs considering local conditions. Many variables at the city-catchment (CC) level influence city hydrological typologies. Ten attributes considered pivotal for defining the scale of the UWS were selected. When considering site-neighbourhood (SN) conditions, eleven variables were considered for setting WMU scales. Some of the selected variables were analysed together since they present effects on WMU scale selection that are highly linked to each other, making it hard to evaluate them separately. All variables, at CC and SN, and their effects on scale recommendations are shown on Table 2.

The CC variables influencing the UWS scale include the following: **(i)** sea proximity (coastal or inland) refers to the city position within the river basin, whether upstream or downstream, and whether the catchment outlet is a river or ocean; **(ii)** freshwater source characteristics refer to the user's proximity and quality of freshwater resources, expenses required for transport and treatment, and added environmental costs; **(iii)** climate and water for (non)consumptive uses refer to the rainfall pattern and available freshwater, which characterize the allowed dependency degree of the city on natural water sources; **(iv, v)** city human density and economic profile are related to the citizens' water consumption pattern, as well as population distribution and density impact, especially on the energy demand for supply distribution and wastewater collection; **(vi)** topography expresses the degree to which topographical variations impact the pumping demand of the whole system; **(vii)** the energy matrix source/electrical grid represents how clean, or carbon-based, energy used in the UWS affects greenhouse gas (GHG) emissions; **(viii)** social awareness reflects citizens' behaviours and political strategies and the commitment level of a city to improving resilience; **(ix)** water quality requirements refer to the legal framework under which utilities and users are subjected to supply water and discharge; and **(x)** the actual state of the UWS refers to the need to expand the system's coverage and retrofit existing WMUs and networks that interconnect them. Planning the scale must consider the baseline conditions to take better profit from the already-made investments. Additionally, the utility experience with smart sensor networks will impact the available database, which is necessary to understand supply demand and wastewater generation patterns and could help in the transition to a more decentralized UWS.

Concerning the scale and site suitability of WMUs, considering SN conditions, **(i)** water quality requirements affect scale differently across the urban fabric. This influences the selection of appropriate sites for installing autonomous DWMUs, which need to discharge some portion of the water (either a reclamation facility or water/wastewater/stormwater management unit) to aquifers or watercourses next to the facility. A contamination risk assessment must be considered; **(ii)** the actual state of the UWS also influences the optimal scale of WMUs across the city differently. This is related to the economies of density when placing DWMUs. When the goal is to promote the transition to a circular and more decentralized UWS, the density of DWMUs must be considered. For example, findings on the tasks carried out by specialized external contractors who travel to treatment plants, empty residuals, or assist with repair and monitoring, indicate that costs would be very high in the case of low-density adoption of distributed systems, and average economies of density diminish for values equal to 1.3 DWMUs/km^2 or above [52]. This suggests that priority must be given to the modular adoption of DWMs, where incentives are provided at the neighbourhood scale, to avoid the sprawl effect, which can increase costs. Therefore, the placement of DWMUs should define target areas to avoid sprawling those treatment facilities; **(iii, iv, v)** growth pattern, land use, and building type refer to the varying interactions between citizens, their activities, and how water consumption/generation patterns vary at land parcels due to different building types [31,37,38]. For example, considering land use scenarios, three main types of land use represent intense occupation patterns that favour decentralized systems, namely, underserved residential neighbourhoods, mixed-use development, and industrial areas [31]. Underserved low-income areas are considered because decentralized systems that replace or fix the actual water infrastructure closer to its source could provide long-term cost savings. Mixed-use development is a more compact urban design that can exploit surplus residential greywater and commercial deficits. Consequently, it requires shorter water networks and offers a greater opportunity to adopt sewage heat recovery and enhance greywater treatment efficiency. Additionally, the industrial water demand can frequently be satisfied by lower-water quality from stormwater harvesting and greywater for the NPR; **(vi)** the percentage of impervious surface: SN conditions that present a high portion of the sealed area and the low presence of green draining DWMUs exhibit greater runoff production entering the drainage subsystem. Furthermore, areas with stormwater connections to pervious land, here understood as green-DWMUs, can maintain better ecological conditions than those directly drained to pipes. Therefore, areas with low to moderate urbanization levels, which have impervious surfaces of up to 25%, present diverse water ecological statuses [40] in the face of the presence of buffering pervious areas; **(vii, vii, ix)** social vulnerability, human density, and green infrastructure coverage:

these variables should be considered when placing green-DWMUs to manage water while promoting distributive green social justice. Higher-density areas are a priority because a greater number of citizens would benefit. Moreover, areas with greater societal challenges related to social vulnerability are a priority for equitable justice, reducing the vulnerability of the most needed areas. Additionally, these areas present lower land prices for installing DWMUs. Above all, green coverage must be considered; that is, sites considered uncovered due to their location being very distant from green-blue spaces should be considered a priority. Other aspects related to ecosystem services (ESs), such as urban heat island reduction, should be considered when placing green-DWMUs [20,68,69]; **(x, xi)** Hydrological draining zone and elevation profile: DWMUs for local source control are more effective options if the intention is to reduce water flooding before runoff enters the drainage systems; they help to minimize pluvial flooding, protect headwaters, and promote aquifer recharge, while larger WMUs, such as ponds or underground water tanks, are a much more effective option if the intention is to reduce flooding in downstream areas and mitigate fluvial flooding [70]. The consideration of those variables depends on the purpose of the WMU.

In summary, to determine the scale of WMUs for drainage, different strategies must be implemented, considering the alignment between urban-subcatchment requirements (SN conditions) and the overall CC needs [47], since the latter governs the main goals desired for the specific UWS being designed. SN conditions can help define scale suitability and priority sites for DWMUs or CWMUs, while CC variables help to define the total amount of flow treated by centralized or decentralized facilities, which produces macro implications over the whole UWS.

Table 2. Scale recommendations for establishing different UWS schemes considering the environmental aspects at two hierarchical levels (city-catchment and site-neighbourhood).

EA [1]	EHL [2]/Ref.	Scale Recommendation
Sea proximity	CC [5,12,71,72]	The scale of WMUs for circularity purposes must consider keeping ecological river flow downstream at inland cities, while coastal cities should avoid discharge since costs and energy demand for desalination are greater than treatment to reuse. Coastal cities can associate reuse and desalination in CWMU for cost efficiency, while inland cities are optimal for various scales, considering discharge implications in the river flow quantity downstream for ecological reasons and possible unplanned water reuse.
Freshwater source characteristics	CC [5,71,73,74]	Diversifying scale for circularity purposes is more advantageous the more distant and deeper are freshwater sources that feed the centralized scheme, due to its increased costs with infrastructure and energy (pumping and piping). Likewise, lower quality of water sources (such as seawater) requires higher costs for treatment. Therefore, encouraging scale diversification to promote circularity.
Climate	CC [5,37,75,76]	The more severe the climate conditions are, the higher the need for scale diversification to close water loops. Cities with high water stress must avoid water storage reliance on rainfall behaviour. This can be achieved through the diversification of the water portfolio (many waters at many scales), prioritizing reuse and the right water for the right use and avoiding energy expenses to a higher quality than needed. Moreover, green-DWMUs can deliver ES and promote adaptation to heat island effects. The latter, during droughts, to continuously deliver ES needs irrigation, only sustainable when based in DWMUs for local nonpotable reuse.

Table 2. *Cont.*

EA [1]	EHL [2]/Ref.	Scale Recommendation
City human density and economical profile	CC [32,37,38,52,77,78]	City human density influences the portion of the system flow that should be treated by CWMUs or DWMUs. Lower-density cities increase costs in conveyance, tending towards an increase in DWMUs. Human density has shown a greater effect than topography on the optimal scale. Moreover, population impact projections of future water needs. Complementary, the city's economic profile (e.g., industrial, tourist-oriented, or next to agriculture fields) influences the presence of certain users that demand high water flows per capita. This leads to the existence of CWMUs with low serving areas, avoiding conveyance costs while maintaining economies of scale.
Topography (steep or flat)	CC [36–38,42,71,73]	Higher pumping costs due to terrain conditions (such as steeper cities) encourage the adoption of HUWS with larger flows being treated by DWMUs. This will reduce conveyance distances and, consequently, the pumping due to high topographic complexity.
Energy matrix source/Electrical grid	CC [76,79–82]	The optimal scale must consider water needs and energy demand for running the whole UWS and each WMU. In the case of a low carbon-based energy matrix, systems can afford higher energy-intensive transport and treatment systems since they do not implicate high environmental impact due to GHG emissions. Moreover, systems should select the best technology alternative to expand the energy recovery capacity both at small (ex: thermal energy recovery) and larger scales, as well as increase green-infrastructure carbon storage capability. Since the energy demand for circular loops is clean, the optimal scale selection will favour the reduction in other resources withdrawal,
Social awareness	CC [66,67]	Attitudes towards setting system scales are shaped by various factors, including awareness of water scarcity, perception of risks and costs, trust in science, and the social influence of relevant agents. Society engagement and implication are also important when managing DWMUs and defining responsibility roles.
Water quality e requirements	CC/SN [5,12,31,36,39,71,72,83]	Water quality requirements vary according to the legal framework, and water sensitivity to discharges. For example, high discharge standards or higher requirements for centralized supply systems increase treatment baseline costs and energy requirements, subsequently lowering the required additional costs for water reuse. Emphasis should be placed on low and medium-scale nonpotable reuse (NPR) facilities, which can lower pumping costs through dual piping systems and treatment expenses compared to potable reuse facilities. This context variable has not only macro implications at the city scale but also at SN. That is because autonomous DWMUs need to discharge some part of the treated wastewater/stormwater to aquifers or watercourses next to the facility. For example, green-DWMUs must consider the risk of contaminating aquifers, as well as avoid shallow underground water.

Table 2. *Cont.*

EA [1]	EHL [2]/Ref.	Scale Recommendation
Actual state of the UWS	CC/SN [42,52–54,59]	System scale for circularity purposes is largely determined by existing infrastructure. HUWSs should take advantage of retrofitting investments due end of central WMUs' lifespan or piping restorations. Additionally, considering the SN level, the management of DWMU presents economies of density. Therefore, the placement of DWMUs for the water/wastewater subsystems should be sectorized through planned target areas, to reduce operational costs. Moreover, HUWS should consider the adoption of smart-water networks to increase redundancy. The utility baseline conditions of the sensors network and. high-tech infrastructure experience not only influence the ability to adopt smart water grids but also provide the database to assist the transition to higher decentralization levels of the system. For example, historical data on water demand, wastewater generation or rainfall overflows, through sensors at strategic points of the network, would allow to structure cluster zones to be served by DWMUs areas.
Growth pattern (compact, sprawl), land use (socioeconomical activities) and building type	SN [31,32,36–38,59]	In suburban, sprawl-occupied areas, individual solutions and other smaller-scale solutions are more appropriate, while in dense areas, the benefits of economy of scale increase, tending to larger-scale WMUs. Mixed-use development requires shorter water networks and offers a greater opportunity for heat recovery, and industrial water demand is frequently satisfied by lower-quality standards. High-rise buildings could employ middle-scale DWMU with lower treatment unit costs than single dwellings. These aspects influence the water-energy (WE) nexus, by finding the optimal scale in between extremes, where the total costs of conveyance and treatment are the lowest. To reduce operational and energy costs to reach water quality requirements, mixing must be avoided before coming into treatment. Therefore, decentralization in areas with specific contaminants generation should be considered. For example, industrial polygons are a priority to reduce mixing with urban wastewater.
Percentage of impervious surface	SN [40,77,84]	Runoff flow pressure in the drainage subsystem is affected by total impervious surfaces, turning areas more vulnerable to extreme rain events. To reduce runoff pressure at the drainage subsystem it is important to promote permeable DWMUs while reducing resident impervious surface footprint. Furthermore, reducing the portion of impervious surfaces indirectly connected to underground pipes, using buffer green-DWMUs (small sized green zones), would also reduce total runoff.
Social vulnerability, human density, and green-infrastructure coverage	SN [20,68,69]	To improve distributive environmental justice, green-DWMUs should be promoted where the population is living far from recreational green spaces, using as criteria the maximum walking distance to green patches suggested by authorities. Additionally, priority must be given where a greater number of citizens (higher sector human density) can be benefited. Moreover, cost benefits are higher in low-income areas. This can be attributed to lower land prices for installing GI and vulnerability reduction where societal challenges are higher.
Hydrological draining zone and elevation profile	SN [30,58,69,85]	Soil drainage capability, erosion vulnerability, hillslope stability, and the hydrological zone should be considered when placing green and/or permeable WMUs. The scale at upstream and middle zones should be smaller, while downstream areas require larger-scale facilities

Notes: [1] EA: Environmental aspect; [2] EHL: environmental hierarchical level, city-catchment (CC), site-neighbourhood (SN).

3.5. Optimal-Scale Studies

As seen, the optimal system scale depends on the costs and energy demands of treatment processes and context variables, such as local topographic, demographic, and hydrologic characteristics; energy conveyance requirements; water demand projections; and baseline investments in centralized systems [22,36,38,42,76]. Many studies that define optimal scales are based on life cycle analysis (LCA) [33,37,45,55], techno-economic assessment [59,86], sustainability index of different scenarios [87], and optimization models [36,38,42,52,61]. In these studies, a central-scale trade-off is highlighted; while centralization favours economy-of-scale treatments, it requires much investment in capital and operational costs for pipelines to meet conveyance needs, especially for the reuse of reclaimed water [32,33,39,42,55,88].

For example, ref. [55] compared four different scales and concluded that reclamation and reuse of greywater at the cluster level was the best option among the three reuse options, although middle and extreme decentralization scale alternatives were more socially beneficial. Compared to the other two centralized alternatives, the main advantages of the cluster level were water savings, community engagement, and urban landscaping. [37] assessed the location and scale of NPR and discovered that for high-elevation areas far from centralized treatment plants (2000 m^3/day), decentralized NPR (20 m^3/day) could lower energy use by 29%, but in low-elevation areas close to centralized treatment plants, decentralized reuse could increase energy demand by up to 85%.

The technoeconomic assessment of three different scale approaches (a centralized, hybrid scheme based on decentralized treatment of black water, together with centralized treatment of greywater, and decentralized treatment of grey and black water) showed that extending sewage connections to a distant treatment facility is less costly than doubling the pipeline at the household level. Results highlight that pipelines govern economies of scale. The decentralized configuration has just been shown to be advantageous (5% less expensive) once the potential energy offset derived from biogas production was included in the analysis [59].

Technoeconomic feasibility was evaluated for five different technology schemes applied at six different scales ranging from 2.3 inhabitants to 300 inhabitants in high-rise housing decentralized configurations. The total cost ranged as a function of the treatment technology and the scale. The most expensive of the presented decentralized systems is shown to be competitive with the cost of water in wealthier regions if more than 100 inhabitants are served [86].

The sustainability of four wastewater management alternatives was compared using a composite indicator that included total annual equivalent costs, carbon emission intensity, eutrophication, and resilience [87]. The four alternatives are two centralized schemes based on different technologies (activated sludge and membrane bioreactor), a decentralized scenario, and a hybrid alternative, which treats black water locally and sends greywater to a central plant. The decentralized and hybrid alternatives showed better performance in terms of carbon emission intensity and resilience, but had higher overall costs associated with source separation and eutrophication potential.

The effects of three different scales on 27 scenarios were studied [38], considering different topographies and human densities, and it was concluded that higher topographic complexity also favoured decentralized systems, while higher human density reduced energy demand in both centralized and decentralized arrangements, generating a greater impact on the cost curve than did topography. However, when accounting for hot water energy savings, the model indicated that the unit water cost did not increase significantly until plant service areas fell below 100 to 1000 homes. The optimal scale increased with human density, reaching 3333 homes per treatment plant. The results also showed that direct potable reuse (DPR) was too expensive for low-density populations and more appropriate for urban settings serving more than 100 residences, especially when considering potential energy savings from recovering hot water. Ref. [42] developed cost functions for both the capital and O&M costs of different water technologies and contrasted them with those of ten DPR plants, revealing economies of scale for many treatment units. The study highlighted how operating costs for collection/distribution networks counterbalanced these economies in centralized systems, citing that in the US, 80% of the sewage energy demand is for conveyance, which consumes on average four times the energy of treatment. Conveyance can reach 39.5 times the energy needed for treatment if regions that suffer from water stress are considered.

To find the optimal scale, ref. [61] developed a heuristic model based on the shortest path and agglomerative clustering algorithm; the findings were that the optimal degree of centralization decreased with increasing terrain complexity and settlement dispersion, and the effect of the latter exceeded that of topography [33]. LCA was used by [33] to compare resource recovery through a centralized scenario and a hybrid scenario where black water was managed in a decentralized facility and greywater was managed for fertilizer production in a centralized unit. For all LCA categories, the total loads of the hybrid scenario were lower than those of the centralized scenario. The major reductions ranged from 66.7 to 74.8% and were shown for fossil resource scarcity, followed by terrestrial, marine, and freshwater ecotoxicity.

On the other hand, ref. [45] reported that centralization benefited resource recovery by reducing energy demand and the carbon footprint. However, the community scale was shown to have the lowest eutrophication potential. A review on the same topic by [32] concluded that economies of scale were largely present in the processing of wastewater and biosolids; however, the redistribution of reclaimed water exhibited diseconomies of scale as water networks increased in service size. When averaged and categorized by scale, the greenhouse gas emissions for large-scale water reclamation systems were significantly lower than those for medium- and small-scale systems. For reclaimed water distribution, her review revealed that decentralized systems exhibited lower (three articles), similar (two articles), or higher (two articles) distributions. The main conclusion of the review is that a centralized arrangement is preferred when higher flow rates of reclaimed water are transferred over shorter distances to fewer end users, and diseconomies of scale are exhibited when the distribution covers a large service area.

Overall, a potable water supply, such as DPR, is less recommended than NPR for decentralized systems, primarily due to its higher treatment costs, operational hurdles, risks of system failure, and potential water quality concerns [23,38,46,89]. Nevertheless, intermediate-scale systems, such as cluster-level setups with qualified personnel that are managed by specialized companies, can be suitable for potable water reuse depending on the surrounding environmental factors [39].

Based on many studies of the optimal scale and accounting for the unique attributes of each case, some scale approaches are more adequate for certain environmental conditions or technology techniques than others. The results indicate that economies of scale apply to many unit processes. However, capital and operational costs related to scale can change as a function of the techniques and technologies applied by the WMU. Thus, based on previous findings, some recommendations are presented in Table 3.

Table 3. Recommended optimal scale considering certain environmental and system scheme conditions.

Scale	Environment Condition/Technology Technique	References
MS [2]/D [1]	Adequate for NPR at high-elevation areas far from the treatment plant designed for water supply. Smaller-scale systems are usually preferred at NPR systems. Additionally, smaller-scale systems present more advantages due to the lower costs and resources necessary to reach desired reuse standards	[37,46]
MS/C [3]	Low-elevation areas close to the treatment plant	[36]
MS/C	High human density favours both approaches, although it increases the optimal scale	[38]

Table 3. *Cont.*

Scale	Environment Condition/Technology Technique	References
MS/C	More adequate for DPR due to higher energy requirements for treatment and greater treatment economies of scale impact while not requiring dual pipe system to water supply distribution	[42,89]
MS	More appropriate for hot water savings at DPR systems	[38,46]
D	Adequate for thermal energy recovery in cold climates due to residential energy demand reduction, resulting in low payback time	[46]
C	High flow rates transfer over short distances	[46]
D	For water distribution or collection covering large and distant service areas	[46]
MS/D	Recommended at more scarce regions that must ensure a more diversified water portfolio and where usually high amounts of freshwater sources are far located from end users	[80]
C	More adequate for hydropower generation that requires high flow rates and elevation drop and for biogas production through biosolids management	[46]
D	For urine source separation, technologies have exhibited higher recovery rates and lower environmental and economic impacts compared to conventional large-scale treatment	[46]
MS/D	Adequate for NPR at high-elevation areas far from the treatment plant designed for water supply. Smaller-scale systems are usually preferred at NPR systems. Additionally, smaller-scale systems present more advantages due the lower costs and resources necessary to reach desired reuse standards	[37,46]
MS/C	Low elevation areas close to the treatment plant	[36]
MS/C	High human density favours both approaches, although it increases the optimal scale	[38]
MS/C	More adequate for DPR due to higher energy requirements for treatment and greater treatment economies of scale impact while not requiring dual pipe system to water supply distribution	[42,89]
MS	More appropriate for hot water savings at DPR systems	[38,46]
D	Adequate for thermal energy recovery in cold climates due to residential energy demand reduction, resulting in low payback time	[46]

Notes: [1] D: Decentralized, [2] MS—Middle Scale, [3] C—Centralized.

4. Discussion

Scale classification (either at the system or unit level) varies among authors. The classification should serve all subsystems of the UWS—WSS, WWS, UDS—avoiding multiple classifications and providing greater comprehension between professionals when transferring knowledge from one to another. This article introduces a new method of classifying scales, differentiating the scale for the entire UWS and the scale of each WMU itself. (Figure 4). When considering the whole system, UWSs can be classified as *centralized*, if the total flow entering the system is managed by large central plants; *decentralized*, when all the flow is managed by autonomous DWMUs (with zero interconnectedness between facilities); and *hybrid*, when part of the flow is managed by CWMUs and the rest by DWMUs. Concerning the unit level, the scale of each WMU was classified (Table 4), considering thresholds defined by the scientific literature and the European wastewater proposal from 2022. Thus, WMUs are categorized in terms of inhabitants (inh.), people equivalent (p.e.), flow (m^3/s) or area of drainage (Ad) in hectares (ha), as follows:

(i) **Onsite individual decentralized units:** serving $1 \leq$ p.e ≤ 40 inh./p.e.; On-source drainage—Ad < 2/3 ha

(ii) **Urban cluster/medium-scale decentralized units:** serving 40 < inh./p.e. < 1000; Conveyance control drainage—2/3 ha < Ad < 3/4 ha

(iii) **Small urban agglomeration decentralized units:** serving 1000 $\leq$ inh./p.e < 10,000; End-of-pipe urban drainage and satellite facilities: 3/4 ha < Ad < 10 ha

(iv) **Medium-scale centralized units:** serving 10,000 $\leq$ inh./p.e. < 100,000; and drainage in between 10 ha < Ad < 8.5 km^2

(v) **Large-scale centralized units:** serving inh. or p.e. $\geq$ 100,000; drainage area with Ad > 8.5 km^2

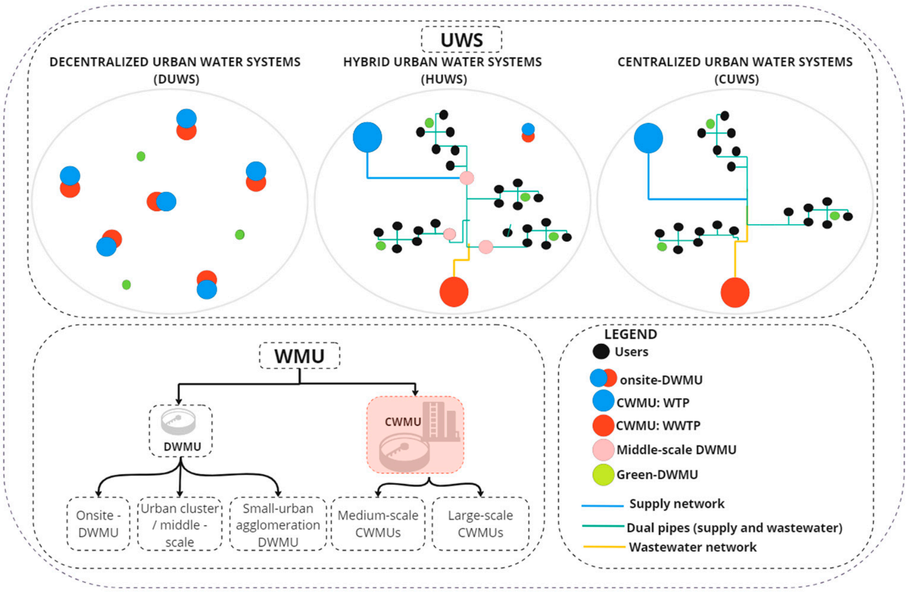

Figure 4. Scale in terms of WMU and UWS.

Table 4. Scale classification of urban water management at the macro (UWS) and micro (WMU) levels.

Scale Level	Scale Classification		Coverage of Service (inh./p.e./Area of Drainage)
Scale of UWS (based on CC conditions at the macro-level)	Centralized Urban Water Systems (CUWSs)		The total flow entering the system is managed by large central plants; The system is designed considering that each user must be connected to a central network that diverts the flow to or from CWMUs
	Hybrid Urban Water Systems (HUWSs)		Part of the flow is managed by CWMUs and others by DWMU; some users are connected through smaller networks and others are connected to networks of greater extent, which connect distant users to larger CWMUs.
	Decentralized Urban Water Systems (DUWSs)		The flow is managed by autonomous DWMUs (with zero interconnectedness between facilities);
Scale of WMU (based on SN conditions at the micro-level)	CWMU	Large-scale CWMUs	Serving inh. or p.e. $\geq$ 100,000; drainage serving Ad > 8.5 km^2
		Medium-scale CWMUs	Serving 10,000 $\leq$ inh./p.e. < 100,000; drainage serving 10 ha < Ad < 8.5 km^2
	DWMU	Small-urban agglomeration DWMU	Serving 1000 $\leq$ inh./p.e. < 10,000; End-of-pipe urban drainage or satellite facilities: 3/4 ha < Ad < 10 ha
		Urban cluster/middle-scale DWMU	40 < inh./p.e. < 1000; Conveyance control drainage: 2/3 ha < Ad < 3/4 ha
		Onsite DWMU	Serving 1 $\leq$ p.e. $\leq$ 40 inh./p.e.; On-source drainage: Ad < 2/3 ha

Decentralization has emerged as a pivotal strategy for harnessing multiple water sources while also enabling the recovery of materials embedded in water and reducing the energy demand associated with water conveyance over long distances. City priorities related to the promotion of circular WMUs for NPR, DPR, IPR, or even unplanned reuse must be very well understood to define which scale is optimal. The transition to decentralized systems is justified by their ability to provide a diversified and climate-independent water resource portfolio, by closing water loops next to the origin and source. Additionally, smaller-scale systems are associated with the greening of cities. The use of green and blue spaces increases the water exchange among urban landscapes, groundwater, and the atmosphere instead of facilitating quick drainage to underground pipes. As a result, the natural compartments of the UWC can be restored.

Nevertheless, centralization is more readily accepted by water managers. It reduces flow disturbances within WMUs and typically results in a lower energy footprint for treatment. This approach presents greater reliability because it is managed by water utilities, which decreases possible public health concerns and flow disturbances; furthermore, centralized schemes are usually preferred for potable water supply due to greater monitoring reliability. CWMUs are also needed for managing stormwater when dealing with high return periods. Conversely, conventional CWMUs supply water for different purposes through the same network. Thus, water is treated to meet drinking water standards, even for nonpotable demand, requiring more energy than it should. The distribution and conveyance costs of circular CWMUs can be reduced when it is possible to deliver high quantities of reclaimed water or recovered material to small areas. In this scenario, larger-scale units are preferred. This can occur in the presence of certain customers who generate and/or consume high amounts of flow. High-flow consumers are related to the city's economic profile and can be situated in urban or peri-urban areas, for example: industries, farmers, hotels, or recreation parks.

The adoption of different scales can potentially influence energy use and circularity loops for water reuse and/or water-embed resource harvesting [80]. Synergies from the interactions between the optimal scale design and the adequate circularity strategy can improve climate change resilience and reduce the depletion of water resources, either by increasing the water portfolio or reducing nonconsumptive uses of low-quality discharge flows. Optimal-scale studies usually point to middle-scale WMUs as the most appropriate solution because they benefit from economies of scale for treatment but are not subject to the larger distances and terrain irregularities that increase conveyance costs.

Since the optimal scale of WMU varies with site and city conditions, the co-occurrence of a diverse range of scales in the same UWS is better than relying on just centralized or decentralized facilities. The combination of both approaches facilitates water management closer to the source and promotes adequate source separation and treatment for NPR while providing high-quality water to treatment plants supplied for potable uses. This raises the concept of HUWS, a strategy that exploits centralized and decentralized WMUs. The HUWS allows the establishment of optimal performance scenarios that can count with multiple waters, local recovery, and usage in the DWMU, while the CWMU serves as a backup treatment for the DMWU, offering more security in the case of failure and an end-of-pipe treatment multi-barrier facility to manage residuals from the DMWU. This multi-barrier approach increases the system's robustness. HUWSs are associated with the concept of multiple waters, as they provide cities with a wide range of water sources and qualities in a sustainable water-secure system [41,43].

This review evaluated trade-offs between different scales of selection for UWSs resilience, by analysing the impacts of scale on the components of resilience capabilities (redundancy, availability, robustness, and learning and investment ability), as well as which UWS functionality (ies) could be involved in the trade-off. Considering the existence of UWS resilience metrics, future studies should focus on the quantitative assessment of these trade-offs, to better evaluate how UWS resilience curves vary at different scale designs.

Scenario assessments varying not only in scale design but also in the circularity approach could generate important insights.

The scale of WMUs and the degree to which UWSs rely on decentralized and centralized facilities are important not only for adapting to water-related risks but also for improving the efficiency of measures to mitigate GHG emissions. The reduction in GHG emissions can be achieved by decreasing energy consumption and recovering energy from wastewater for other uses. To make impactful changes, UWSs must go beyond net-zero and reach surplus energy by improving circularity at many scales in the whole system. Future water services will need to integrate multiple sources, such as freshwater, reuse water, stormwater, groundwater, and seawater, at multiple scales through both centralized and decentralized services.

To evaluate how scale affects UWS resilience, three system metrics that express UWSs functionalities related to resilience were selected. The metrics are net energy, net water, and ecosystem services (Table 5). The scale effect on net energy comes from its impact on the energy demand for pumping, piping, extracting, treating, and recirculating water and its recovery from wastewater, as well as the energy recovered or used to take full advantage of water embedded-materials. Scale also impacts the system's net water, as it influences the location and quantity of discharge flows from WMUs, reduces freshwater withdrawals through fabricated water sources at multiple scales, and affects downstream water quality through distributed or localized discharges (when combined with circular units); scale also impacts rainfall storage capability; and UWS's scale influences the ability to provide system functionalities beyond water services. These functionalities refer to ES capable of improving human well-being, the biological function of cities, or natural source restoration through nature-based WMUs.

Table 5. UWS resilience metrics and description of the impact of scale on UWS functionalities.

UWS Resilience Metrics	Description of UWS Scale Impacts on UWS Functionalities
Net Energy	A scale must be set to optimize UWS energy consumption. Minimal energy consumption based on clean energy should be preferred to reduce GHG emissions.
Net Water	The scale should be set to promote reuse and increase the water portfolio while decreasing water withdrawal. At the same time, the total discharge load decreases, reducing nonconsumptive uses.
Ecosystem services	Nature-based WMUs can provide ecosystem services across the urban fabric and distributed green units, which can be an instrument to provide equitable justice at vulnerable sites while enforcing community cohesion.

The full comprehension of the implications and relationships of scale and its surrounding conditions will usually provide WMUs with different optimal scales across the UWS. Thus, future water schemes should be based on hybrid configurations that include many technologies, ranging from green to grey [14]. These units are designed for water treatment and to improve urban metabolism by reusing water, restoring the water cycle, and recovering resources. All these processes must be facilitated by remote and predictive control based on digital and/or AI-powered solutions. Moreover, the inclusion of socioeconomic and subjective variables ensures that policy recommendations are not only environmentally sound but also socially acceptable, promoting community engagement and improving social justice across cities.

Scale, as a design variable, is constantly associated with other characteristics of UWSs. For example, the need to diversify the water portfolio or recover materials associated with the recovery of other urban metabolic flows refers to the scale of circularity, and in our research, 38 documents from a total of 57 papers would talk about scale in association with circularity. The urgency to provide ecosystem services in cities, to reduce climate effects while managing water more sustainably, and to recover natural parts of the UWC is associated with scale diversification in drainage subsystems and the transition to higher implementation of greening strategies in UWSs. In our review, 22 documents would relate scale to greening. Finally, the need to provide coordination and efficient management between WMUs and smart water grids requires a central control facility supported by a smart sensor network distributed along pipes and the many WMUs that would cover the system, allowing greater redundancy and robustness of the system. In this case, scale diversification demands another improvement in the design of UWSs, which is the digitalization of the system. Our review revealed six documents related to scale and the increased use of digital technologies. Thus, we consider that, if resilience measures need to address multiple functionalities for trade-offs between competing aspects [17], or, further, possible synergies between system functionalities, to improve the comprehension of UWS resilience capacity, future work should focus on four design variables of UWSs, namely: ***scale***, ***circularity***, ***greening***, and ***digitalization***.

5. Conclusions

Scale is crucial in UWS design. Our study underscores the significance of identifying and implementing optimal scales that recognize the trade-offs between centralized and decentralized approaches and how they are affected by the environmental conditions of each city and different locations across urban areas. This article proposes a novel approach for choosing the optimal scale of urban water management and infrastructure, offering a classification at two levels of analysis: the system and the unit level. Then, a qualitative approach was used to reveal the trade-offs between different scales in terms of UWS functionalities; the interplay between scale, system functionalities, and the four selected components (reliability, redundancy, robustness, learning and investment capacity) of resilience capabilities (absorptive, adaptative, and restorative) was also analysed. To understand which is the optimal scale, we divided the analysis into two hierarchical levels: city-catchment and site-neighbourhood. The first level of analysis aims to support the optimal scale definition for the whole system. The second analysis level considers eleven site-neighbourhood environmental aspects to determine the scale and location of each WMU within the system. Considering city-catchment variables allows a full comprehension of the hydrological interactions of a city's metabolism and the river basin where the city is located. Moreover, the second level of analysis allows us to prioritize which city sectors/sites present greater advantages for decentralization and which zones should remain connected to the main central plant. This comprehension also provides insights into future schemes, which could be designed based on resilience metrics that reflect estimations of energy, environmental, economic, and social system performance. The optimal scale definition is a multicriteria decision problem. Therefore, the consideration and weight of each variable for deciding "which scale" depends on the purpose of each WMU, which must be aligned with the more urgent needs of the UWS, and ultimately, it reflects city water needs.

Previous research underscores the significance of understanding the interactions among different system components and functionalities to develop more effective strategies. Therefore, UWS resilience measures need to address multiple functionalities in order to account not only for trade-offs between competing ones but also for possible synergies that arise from the design of the system. For that, future studies are encouraged to delve deeper into understanding the interactions between scale, circularity, greening, and digitalization, which collectively constitute the primary design strategies of UWSs.

Intermediate scales of systems and units, when set to be optimal, have the potential to minimize energy and other resource consumption while enhancing ecosystem services. Decision-makers are urged to integrate elements of both centralized and decentralized approaches into the same system, fostering a HUWS that is designed to achieve net-zero emissions and facilitate circular resource flows beyond water. Optimal configurations must be as dynamic as the problem they aim to solve. Ultimately, the adoption of a low-carbon energy matrix is crucial in the pursuit of net-zero emissions, thereby contributing to broader efforts to effectively address the WEFE nexus and climate change.

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Abbreviations

NPR	Nonpotable Reuse
SN	Site-Neighbourhood
UDS	Urban Drainage Subsystem
UWC	Urban Water Cycle
UWS	Urban Water Systems
WMU	Water Management Units
WSUD	Water Sensitive Urban Design
WSS	Water Supply System
WWS	Wastewater System
CC	City-Catchment
CWMU	Centralized Water Management Units
DWMU	Decentralized Water Management Units
DPR	Direct Potable Reuse
HUWS	Hybrid Urban Water Systems
IPR	Indirect Potable Reuse

Appendix A

Table A1. Keywords used for the QUERY 01, that considered queries for Context AND Resource AND Framework, AND Technology, AND Methods.

AND Query Layers	Layers Keywords
Context	"urban" or "cities" or "city" or "green cit*" or "circular cities" or "Urban greening" or "municipality"))
Resource TS	("Water supply" or "stormwater" or "water reuse" or "reclaimed water" or "residual water" or "sewer" or "runoff" or "wastewater" or "potable water" or "drinking water" or "surface water"
Framework TS	=("Water management" or "Integrated Water Management" or "water-food-energy" or "flood management" or "socio hydrology" or "hydrosonical" or "hydro social" or "stormwater management" or "urban water management" or "Digitalization NEAR/15 water" or "circular economy" or "resilience NEAR/15 water" or "climate change NEAR/15 water" or "risk management" or "climate adaptation NEAR/15 water" or "transition" or "sustainab* challenges" or "water schemes" or "adaption" or "mitigation" or "Social-Ecological Systems" or "Scarcity" or "Social injustice" or "resource depilation" or "Human Well-being" or "Sponge Cit*" or "Collaborative planning" or "urban planning"

Table A1. *Cont.*

AND Query Layers	Layers Keywords
	"Water systems" or "system*" or "solution*" or "infrastructure" or "technolog*"or "control" or "sewer network" or "sewer Systems" or "Integrated water systems" or "urban water network" or "urban water systems"))
Technology TS	"hybrid" or "circular" or "green" or "blue" or "grey" or "conventional" or "green-blue-grey" or "BGI" or "Blue-green" or "smart" or "digital" or "digital twin*" or "Water-sensitive urban design" or "Sustainable urban water management" or "sustainable urban drainage" or "SUDS" or "LID" or "low impact development" or "reuse" or "combined sewer overflow" or "CSO" or "drainage solution*" or "Nature-based solution*" or "NBS" or "*centralized" or "*centralised" or "green-blue" or "gray" or ("Resource recovery" and "wastewater") or "high tech" or "high touch" or "green urban infrastructure" or "GUI" or "information and communication Technology" or "ICT" or "resource recovery" or "circularity" or "renaturization" or "BMPs" or "whud"))
Research Approach TS	("environmental" or "social" or "hydrogeological" or "water quality" or "land") and ("*benefit*" or "impact" or "performance" or "need*" or "requirement*")) or "challenges" or "Key performance indicators" or "KPI" or "indicators" or "risk reduction" or "efficiency" or "ecosystem services" or "Effectiveness" or "hazard" or "index" or "TRL" or "Technology Readiness Levels" or "CAPEX" or "OPEX" or "scale" or "MCDA" or "GIS" or "spatial footprint" or "footprint" or "advantages" or "disadvantages" or "design" or "location" or "unit cost" or "cost" or "stakeholder* perception*" or "social value"))
Methods TS	"systemic" or "review" or "integrated method*" or "planning tool" or "planning-support tool" or "Cost effectiveness" or "Cost-benefit*" or "CBA" or "life cycle assessment" or "LCA" or "assessing" or "impact asses*" or "analysis" or "comparison" or "impact" or "performance" or "evaluat*" or "State-of-the-art" or "suitability" or "decision support system" or "analytic hierarchy process" or " life cycle costing" or "barriers" or "opportunities" or "trade-offs" or "synergies" or "co-benefit*" or "modelling" or "Planning support systems" or (("site" or "solution" or "technology" or "place*") and ("prioritization" or "ranking")) or "pathways" or "scenario*"))"
General Interest * TS	=(("health" OR "well being") AND ("review" OR "overview") AND ("urban") AND ("green justice" OR "green spaces" OR "Socio-environmental justice"))

Note: * OR layer.

Research Query of the Main Review

(((((((TS = ("urban" or "cities" or "city" or "green cit" or "circular cities" or "Urban greening" or "municipality")) AND TS = ("Water supply" or "stormwater" or "water reuse" or "reclaimed water" or "residual water" or "sewer" or "runoff" or "wastewater" or "potable water" or "drinking water" or "surface water")) AND TS = ("Water management" or "Integrated Water Management" or "water-food-energy" or "flood management" or "socio hydrology" or "hydrosonical" or "hydro social" or "stormwater management" or "urban water management" or "Digitalization NEAR/15 water" or "circular economy" or "resilience NEAR/15 water" or "climate change NEAR/15 water" or "risk management" or "climate adaptation NEAR/15 water" or "transition" or "sustainab* challenges" or "water schemes" or "adaption" or "mitigation" or "Social-Ecological Systems" or "Scarcity" or "Social injustice" or "resource depilation" or "Human Well-being" or "Sponge Cit*" or "Collaborative planning" or "urban planning")) AND TS = ("Water systems" or "system*" or "solution*" or "infrastructure" or "technolog*"or "control" or "sewer network" or "sewer Systems" or "Integrated water systems" or "urban water network" or "urban water systems")) AND TS = ("hybrid" or "circular" or "green" or "blue" or "grey" or "conventional" or "green-blue-grey" or "BGI" or "Blue-green" or "smart" or "digital" or "digital twin*" or "Water-sensitive urban design" or "Sustainable urban water management" or "sustainable urban drainage" or "SUDS" or "LID" or "low impact development" or "reuse" or "combined sewer overflow" or "CSO" or "drainage solution*" or "Nature-based solution*" or "NBS" or "*centralized" or "*centralised" or "green-blue" or "gray" or ("Resource recovery" and "wastewater") or "high tech" or "high touch" or "green urban infrastructure" or "GUI" or "information and communication Technology" or "ICT" or "resource recovery" or "circularity" or "renaturization" or "BMPs" or "whud")) AND TS = ((("environmental" or "social" or "hydrogeological" or "water quality" or "land") and ("*benefit*" or "impact" or "performance" or "need*" or "requirement*")) or "challenges" or "Key performance indicators" or "KPI" or "indicators" or "risk reduction" or "efficiency" or "ecosystem*

services" or "Effectiveness" or "hazard" or "index" or "TRL" or "Technology Readiness Levels" or "CAPEX" or "OPEX" or "scale" or "MCDA" or "GIS" or "spatial footprint" or "footprint" or "advantages" or "disadvantages" or "design" or "location" or "unit cost" or "cost" or "stakeholder perception*" or "social value")) AND TS = ("systemic" or "review" or "integrated method*" or "planning tool" or "planning-support tool" or "Cost effectiveness" or "Cost-benefit*" or "CBA" or "life cycle assessment" or "LCA" or "assessing" or "impact asses*" or "analysis" or "comparison" or "impact" or "performance" or "evaluat*" or "State-of-the-art" or "suitability" or "decision support system" or "analytic hierarchy process" or " life cycle costing" or "barriers" or "opportunities" or "trade-offs" or "synergies" or "co-benefit*" or "modelling" or "Planning support systems" or (("site" or "solution" or "technology" or "place*") and ("prioritization" or "ranking")) or "pathways" or "scenario*")) OR TS = (("health" OR "well-being") AND ("review" OR "overview") AND ("urban") AND ("green justice" OR "green spaces" OR "Socio-environmental justice"))*

Table A2. Keywords used for the QUERY 02, that considered queries for Funding Source AND Research interest.

AND Query Layers	Layers Keywords
Funding FT	"NATURANCE" OR "ThinkNature" OR "EKLIPSE" OR "OPPLA" OR "UNaLAB" OR "RCC-BrownMON" OR "UrbanGreenUp" OR "GrowGreen" OR "NATURVATION" OR "Nature4Cities" OR "ClimateKIC ACT on NBS" OR "EU Smart Cities Information System" OR "SCIS" OR "COST Action Circular City" OR "CLEaN-TOUR" OR "Closing material flows by wastewater treatment with green technologies" OR "UFR" OR "Urban health cluster" OR "Phusicos" OR "CRC for water sensitive cities" or "RCC-BrownMON: Urban Water Cluster" or "Clean & Circle Project" or "HYDROUSA" or "KURAS" or "C2C-CC" or "NICE" or "UK Natural Environment Research Council"or "US National Science Foundation" or "National Science Foundation Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure")) AND TS = ("stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid*" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water"
Research Interest TS	"stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid*" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water"

Note: asterisks denote a truncated version of the keywords used.

Funding Research Query

(FT = ("NATURANCE" OR "ThinkNature" OR "EKLIPSE" OR "OPPLA" OR "UNaLAB" OR "RCC-BrownMON" OR "UrbanGreenUp" OR "GrowGreen" OR "NATURVATION" OR "Nature4Cities" OR "ClimateKIC ACT on NBS" OR "EU Smart Cities Information System" OR "SCIS" OR "COST Action Circular City" OR "CLEaN-TOUR" OR "Closing material flows by wastewater treatment with green technologies" OR "UFR" OR "Urban health cluster" OR "Phusicos" OR "CRC for water sensitive cities" or "RCC-BrownMON: Urban Water Cluster" or "Clean & Circle Project" or "HYDROUSA" or "KURAS" or "C2C-CC" or "NICE" or "UK Natural Environment Research Council"or "US National Science Foundation" or "National Science Foundation Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure")) AND TS = ("stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water")*

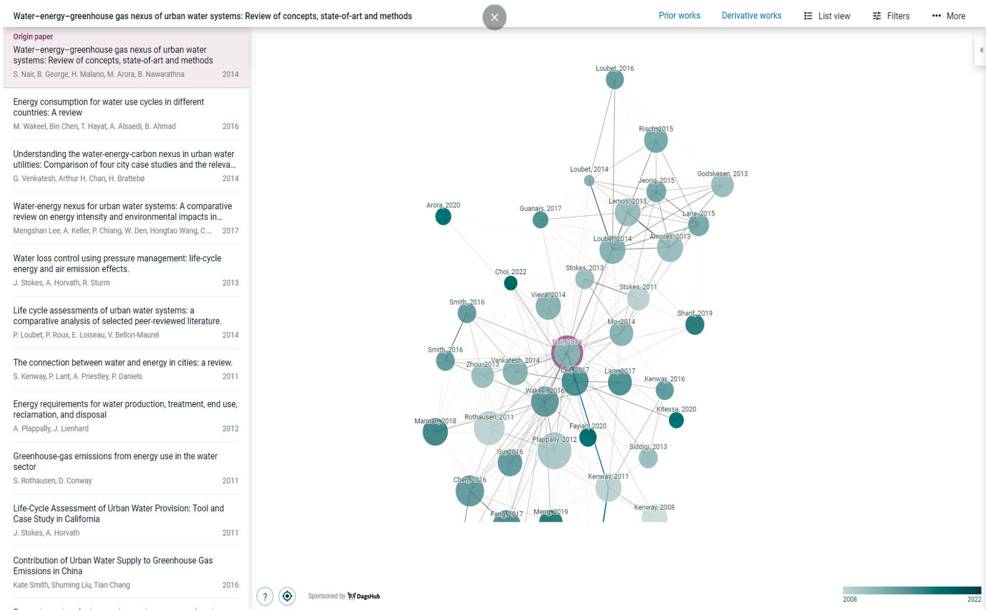

Figure A1. Research tool used for retrieving complementary articles. Access on https://www.connectedpapers.com/ (accessed on 23 October 2023).

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