Exploring Contextual Influences on Scale Suitability of Urban Water Systems: A Literature Review

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Highlights:

- Scale is an attribute inherent to WMU within UWS and assumes different classifications at the unity and system analysis level.
- Eighteen environmental factors affect UWS and WMU optimal scale: ten at the catchment-city level, and eleven at site-neighborhood.
- Scale affects UWS resilience mainly due to impacts on the energy balance, water depletion, and human wellbeing.

Keywords: urban water system; scale of water systems; suitability

INTRODUCTION

The overall arrangement of Urban Water Systems (UWSs) can rather be relied on centralized units, for all types of water streams (supply, wastewater, or stormwater), or it can present water management units (WMUs) covering a diverse range of scales. The challenge lies in defining and quantifying an optimal service area based on population or households served and circularity purposes (Guo & Englehardt, 2015; Kavvada et al., 2018). UWSs, if decentralized, are made by distributed autonomous WMUs. However, in urban environments it is preferred that WMUs work integrated into the centralized network, complementing the existing system, rather than requiring a total system overhaul. This configuration counts with services backup, in case of failure, and is referred to as hybrid urban water systems (HUWSs). Scale substantially impacts how UWSSs are designed and implemented, and a detailed understanding of these effects requires analyses that take a whole-of-system approach. There are many trade-offs when transitioning from small to large scales and vice versa. Which scale is more appropriate under certain conditions? What is the optimal scale at the unity and system level? How do environmental conditions influence optimal scale definition? The objective of this systematic review is to understand how optimal scale varies considering environmental conditions and UWS' services goals (**Figure 1**).

We propose two levels of analysis for defining the optimal scale of urban water management: The first is the city-catchment level, which considers aspects of the city location within the basin and helps identify how macro aspects of the UWSs are affected. The second level refers to the analysis of site and neighborhood aspects, which varies across the urban fabric, and affect the selection of priority and suitable sites according to the scale approach, if is desired centralized (CWMUs) or decentralized WMUs (DWMUs) to compose the water system.

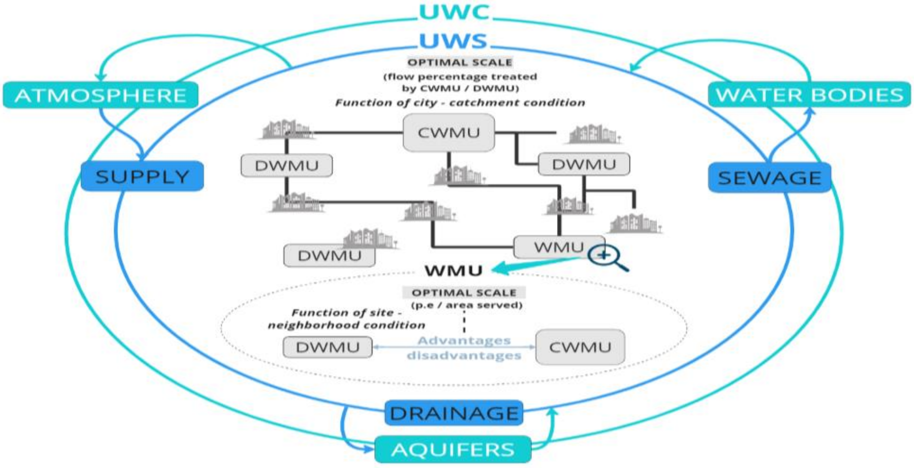

Figure 1. UWS within the UWC. Environmental aspects influence the water management scale of UWSs and WMUs.

METHODOLOGY

The literature related to urban water cycle technologies was retrieved from the Web of Science (WOS) database. The screening process was conducted at two levels: the title and abstract level 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. Complementary articles related to the theme were selected through the machine learning web tool “connected papers”. Overall, a total of 57 articles, reports, and norms were thoroughly reviewed.

RESULTS AND CONCLUSIONS

The comprehension of city-hydrological typology, defined by city-catchment conditions, helps identify how macro aspects of the UWSs are affected. For example, which is the main water source and which amount of the total water flow should be treated by decentralized and centralized facilities. Complementary, site-neighborhood (SN) characteristics are fundamental for defining the scale and site of WMUs within the UWS. The relation between the environmental aspects (EA), correspondent environmental hierarchical level affected, CC and/ or SN, and the scale recommendation considering EA effects on water systems and units were studied. Some EAs highly linked to each other were grouped to simplify their evaluation. The information is as follows (Berbel et al., 2023; Eggimann et al., 2016; Guo & Englehardt, 2015; Kavvada et al., 2018; Lam & Van Der Hoek, 2020; Leigh & Lee, 2019): *(i)**Sea proximity (CC):*** Scale of UWSs at Inland cities should ensure downstream river flow, while coastal cities are advised to integrate reuse and desalination (when needed) in CWMUs for cost efficiency; *(ii) **Freshwater source characteristics (CC)**:* Diversifying scale for circularity purposes is more advantageous the more distant and deeper are freshwater sources, due increased piping and pumping costs;*(iii)* ***Climate (CC):*** Optimal scale adoption must consider climatic conditions, prioritizing reuse, and desalination to address baseline water stress conditions and promote green-DWMUs to adaptation to heat island effects; *(iv)* ***Human density and city economical profile (CC):*** In lower density cities, a larger proportion of the flow is typically treated by decentralized wastewater management units (DWMUs). Meanwhile, larger scale facilities serving small areas are proper for high-water per capita economical consumers; *(v)* ***Topography (CC):*** Steeper cities incur higher pumping costs, favoring the adoption of DWMUs to reduce conveyance expenses; *(vi)* ***Energy matrix source/Electrical grid (CC):*** Optimal scale selection should account for water needs and energy demand, particularly if low-carbon energy sources are promoting systems based on cleaner energy and resource reduction; *(vii)* ***Social awareness (CC):*** UWS scale is shaped by factors like water scarcity awareness, perception of risks and costs, and trust in science, influencing system scale decision; *(viii)* ***Wastewater quality requirement (CC/SN):*** High discharge standards lower additional costs for water reuse, encouraging scale diversification. Cost-effective solutions should focus on low and medium-scale NPR facilities for conveyance and transport cost reduction. DWMUs must consider the risk of contaminating aquifers across different sites of the city; *(ix)* ***Actual state of the UWS (CC, SN):*** Scale diversification costs to promote HUWSs are function of retrofitting needs and sectorization (economy of density) for cost reduction; *(x)* ***Growth pattern, Land use, and building type (SN):*** Consider individual solutions in sprawl areas and centralized systems in dense areas for scale optimization. Mixed-use development and high-rise buildings can benefit from middle-scale DWMUs for cost-efficient treatment; *(xi)* ***Percentage of impervious surface (SN):*** To reduce runoff pressure at drainage subsystem it is important to promote permeable DWMUs while reducing resident impervious surface footprint; *(xii)* ***Social vulnerability, local human density & green-infrastructure coverage (SN):*** Green-DWMUs should be promoted at high density, socially vulnerable areas lacking green spaces. Focus on low-income areas also reduces costs in land acquisition; *(xiii)* ***Hydrological draining zone and elevation profile (SN):*** Soil drainage capability, propension to soil erosion, and hydrological zone should be considered when placing green and/or permeable WMU. The scale at upstream and middle zones should be smaller than in downstream areas, which require facilities capable of managing higher flows.

Our study proposes a novel definition and classification for the scale of water management, distinguishing two levels of analysis: the system, influenced by city-catchment conditions, and the unity level, influenced by conditions at the site-neighborhood. The significance of identifying and implementing optimal scales of water management and infrastructure is underscored, recognizing how they are affected by environmental conditions, and considering different city-hydrological typologies and locations across urban areas.

Table 1. UWS within the UWC. Environmental aspects influence the water management scale of UWSs and WMUs.

Environmental Aspect (hierarchical level)	Scale recommendation
Sea proximity (CC)	Scale of UWSs at Inland cities should ensure downstream river flow, while coastal cities are advised to integrate reuse and desalination (when needed) in CWMUs for cost efficiency
Freshwater source characteristics (CC)	Diversifying scale for circularity purposes is more advantageous the more distant and deeper are freshwater sources, due increased piping, and pumping costs;
Climate (CC)	Optimal scale adoption must consider climatic conditions, prioritizing reuse, and desalination to address baseline water stress conditions and promote green-DWMUs to adaptation to heat island effects;
Human density and city economical profile (CC)	In lower density cities, a larger proportion of the flow is typically treated by decentralized wastewater management units (DWMUs). Meanwhile, larger scale facilities serving small areas are proper for high-water per capita economical consumers;
Topography (CC):	Steeper cities incur higher pumping costs, favoring the adoption of DWMUs to reduce conveyance expenses;

Energy matrix source/Electrical grid (CC)	Optimal scale selection should account for water needs and energy demand, particularly if low-carbon energy sources are promoting systems based on cleaner energy and resource reduction;
Social awareness (CC)	UWS scale is shaped by factors like water scarcity awareness, perception of risks and costs, and trust in science, influencing system scale decision;
Wastewater quality requirement (CC/SN)	High discharge standards lower additional costs for water reuse, encouraging scale diversification. Cost-effective solutions should focus on low and medium-scale NPR facilities for conveyance and transport cost reduction. DWMUs must consider the risk of contaminating aquifers across different sites of the city;
Actual state of the UWS (CC, SN)	Scale diversification costs to promote HUWSs are function of retrofitting needs and sectorization (economy of density) for cost reduction;
(Growth pattern, Land use, and building type (SN)	Consider individual solutions in sprawl areas and centralized systems in dense areas for scale optimization. Mixed-use development and high-rise buildings can benefit from middle-scale DWMUs for cost-efficient treatment;
Percentage of impervious surface (SN)	To reduce runoff pressure at drainage subsystem it is important to promote permeable DWMUs while reducing resident impervious surface footprint;
Social vulnerability, local human density & green-infrastructure coverage (SN)	Green-DWMUs should be promoted at high density, socially vulnerable areas lacking green spaces. Focus on low-income areas also reduces costs in land acquisition;
Hydrological draining zone and elevation profile (SN)	Soil drainage capability, propension to soil erosion, and hydrological zone should be considered when placing green and/or permeable WMU. The scale at upstream and middle zones should be smaller than in downstream areas, which require facilities capable of managing higher flows

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