



Exploring alternative practices in urban water management through the lens of circular economy—A case study in the Barcelona metropolitan area

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ABSTRACT

Urban water management has recently been questioned because of the fragmented nature of the urban water system and its linear model. The integration and management of water systems are currently recognized as a socio-technical challenge that must be addressed for a more sustainable urban water management. In the short term, a key factor for its transition will be integration of alternative practices that allow for experimentation, learning, and scaling up. This study aims to identify potential shifts supported by two alternative practices for water reuse: nature-based solutions and water reuse technologies, using circular economy principles as analytical categories. The research uses a case study, the Besòs river of the Barcelona metropolitan area, to show that: i) improving biodiversity and water quality helps to regenerate natural capital; ii) water reuse for streamflow augmentation keeps resources in use and promotes synergies, which benefits social livability; and iii) risk management and a potential fit-to-purpose strategy can marginally help to avoid waste externalities. This research has shown that the CE principles are applicable as a framework for identifying the interconnected shifts promoted by water systems. A reflexive understanding of the alternative practices provides deeper insight into the experiences, barriers, and shifts that allow innovative interactions in specific urban contexts and can deliver additional benefits for society. This knowledge can be useful for integrated urban management; however, further integration of cross-sectoral collaboration and flexibility are required.

1. Introduction

There is growing concern about urban water systems being i) based on linear management models that center on extraction, use, and disposal, and ii) dependent on large-scale and centralized infrastructures and technologies (Heiberg et al., 2020; Hoffmann et al., 2020). This linear model of urban water systems is being challenged for its environmental sustainability, as it may cause the deterioration of water and other resources due to the influential presence of pollutants and waste stocks in the environment that are affecting human and ecosystem health (Fuenfschilling and Truffer, 2014; Nika et al., 2020b). Addressing these issues—for instance, by overcoming the fragmented nature of water management—presents a complex challenge, as urban water systems are socio-technical systems that involve not only actor practices but also the interactions between infrastructures, institutions, and regulations (Fuenfschilling and Truffer, 2014; Nieuwenhuis et al., 2021).

Moving toward an integrated water system has multiple

sustainability challenges, such as how to increase natural capital, close the loops in urban water systems, and avoid negative environmental effects (Fidélis et al., 2020; Hoffmann et al., 2020; Nieuwenhuis et al., 2021). The aim of technical, environmental, and social shifts is to integrate the urban water cycle and system management and thereby create a more sustainable urban water management (SUWM) (Adem Esmail and Suleiman, 2020; Fuenfschilling and Truffer, 2014). As compared to traditional approaches, SUWM is an overarching concept that promotes additional benefits gained through innovation, such as incorporating new ways of addressing water challenges from alternative practices in urban water systems (Adem Esmail and Suleiman, 2020; Marlow et al., 2013).

The term alternative practices is used in this study to refer to the practices that deliver added benefits (such as technical developments and institutional responses) that are typically supported as short-term, singular interventions (Fuenfschilling and Truffer, 2014; Hoffmann et al., 2020). Conditions that support alternative practices include

; SUWM, Sustainable Urban Water Management; CE, Circular Economy; NBS, Nature-based Solutions; WRT, Water Reuse Technologies.

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protected sociotechnical spaces/niches, funded implementation, and research and development; in these conditions, new approaches, technologies, and routines can be tested, and any added benefits of these tests can be determined. Alternative practices may need to be built up to promote systemic changes, such as the emergence of new rules and systems, which would allow fundamental change in water systems over the long-term (Fuenfschilling et al., 2019; Ghosh et al., 2021).

In the short term, implementing alternative practices provides insights about the experiences, barriers, and shifts to be endorsed; this knowledge can help to advance the sociotechnical challenge of system integration and urban water cycle management. Consideration of alternative practices as a means for experimentation, learning, and scaling as proposed by Luederitz et al. (2017) could facilitate operationalization of SUWM. The search for novel approaches and technologies could support new paradigms, such as circular economy (CE), which has been proposed for achieving non-linear systems and transitioning to SUWM (Cipolletta et al., 2021; Hoffmann et al., 2020). Based on the CE paradigm, sustainability of water systems is analyzed based on three guiding principles: i) it regenerates natural capital; ii) keeps resources in use, and iii) it designs out waste externalities (Arup and Ellen MacArthur, 2018).

The gray literature discusses the benefits of CE derived from the value created at synergies between urban systems (Arup and Ellen MacArthur, 2018), and as key building blocks required for a utility to transition (Jazbec et al., 2020). Previous research has reported a link between water systems and CE, leading to the proposal that adopting the CE model could be a potential response to the linear model for a water system transformation (Nika et al., 2020a). Focusing on SUWM also seems to help to incorporate urban water management into the

emerging CE paradigm, by highlighting the role of water reuse on the services that urban water systems are expected to provide (Hoffmann et al., 2020). Specific opportunities for water reuse as substitutions of water resources could include streamflow augmentation, recreational and ecological purposes, greening and cooling, and agricultural irrigation, among others (Hoffmann et al., 2020; Jazbec et al., 2020).

The literature is lacking reports of concrete cases that operationalize the CE principles, actions, and potential circularity features, yet this is needed for identifying incremental shifts towards integration and management of urban water systems. The aim of this research is to identify contributions of alternative practices to SUWM by using a case study that implements two alternative practices addressing water reuse—namely, nature-based solutions (NBS) and water reuse technologies (WRT)—in the Besòs river area of Barcelona metropolitan area (Àrea Metropolitana de Barcelona; AMB) (Fig. 1).

The data collection process for the case study included interviews with different stakeholders, field observation, and a desk review of secondary sources on the alternative practice performance on water reuse. Data analysis was conducted using the CE framework (Table 1). The case study revealed: i) alternative practices that gave an added benefit to the specific urban context, and ii) the practicality of the proposed framework for identifying the incremental shifts promoted in water systems.

In Section 2, we introduce the CE Principles as analytical categories; in Section 3, we describe the materials and methods; in Section 4, we present the findings and discuss the contributions to SUWM; and in Section 5, we present our conclusion.

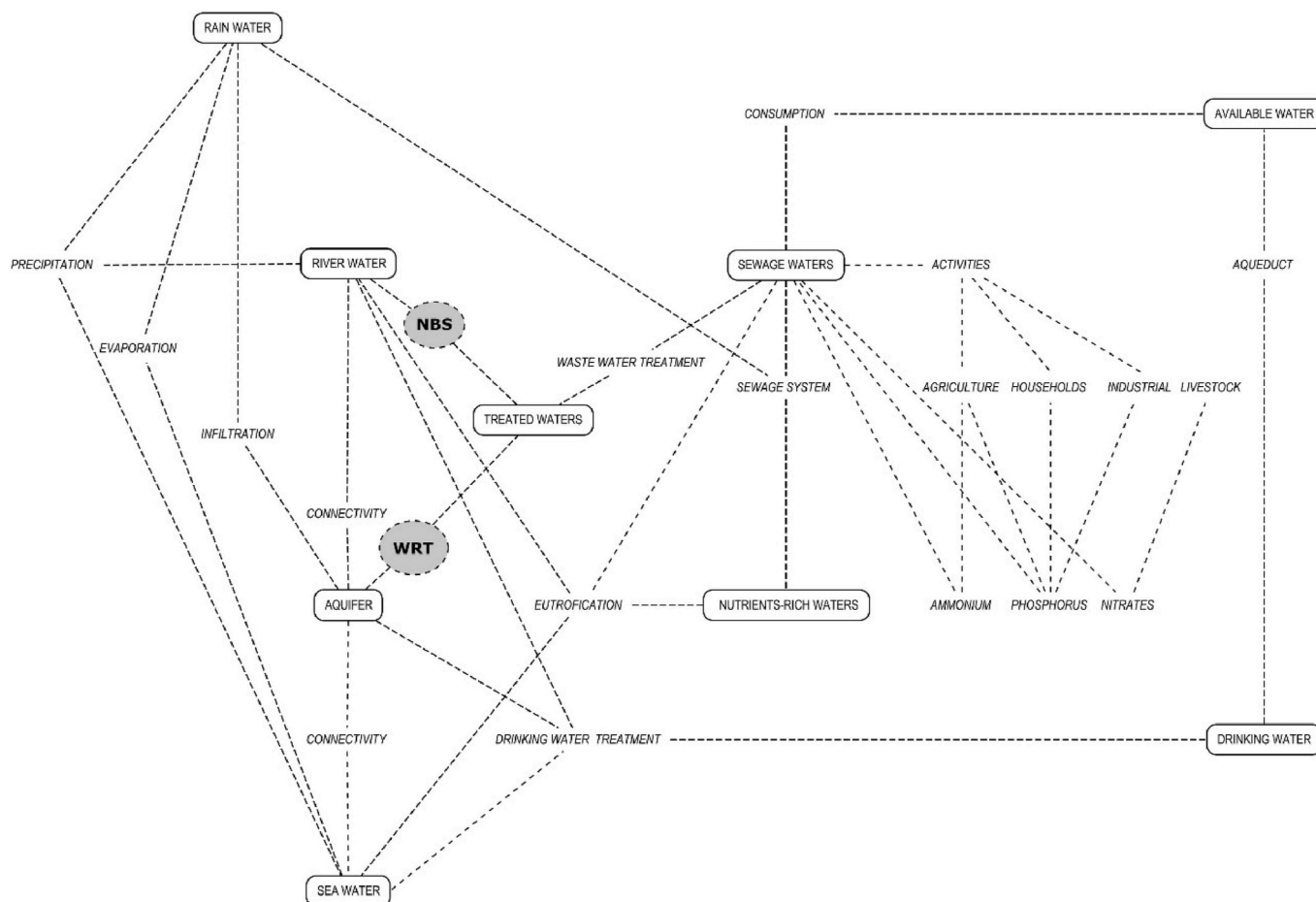


Fig. 1. Graphical representation of the case study and the alternative practices.

Table 1
Framework of the CE principles in water systems: actions and potential circularity features.

CE Principles	Actions	Potential Circularity Features
<i>Regenerate natural capital</i> Preventing pollution and restoring natural capital, to guarantee functional environmental flows and stocks.	Natural capital preservation and enhancement Minimize disruption from human interactions and use of natural water systems	Support the ecosystem's health (biodiversity, greening and cooling properties) Improve the quality of (and reduce) discharge effluents (water quality, waterways, or urban landscapes)
<i>Keep resources in use</i> Maximize water use by maintaining water in the landscape, close resource loops, and preserve its value as long as possible through recovery, reuse, upcycling, and recycling.	Benefits from the value generated in the interface of water systems with other systems Optimize through resource yields obtained within water systems	Reduce water use (streamflow augmentation by returning treated wastewater to waterways, maximizing environmental flows, consumption and non-consumption) Optimize resources via use and extraction of nutrients (N, C, P), minerals, chemicals, and energy
<i>Design out (waste) externalities</i> Design out waste disposal by targeting environmental and social impacts and the economic efficiency of waste reduction.	Address the negative environmental and social impacts Improve efficiency of resources	Risk management (via stormwater attenuation, reduced discharge to the environment, reduced atmospheric emissions, and lower social exposure) Target the most efficient amounts of (fresh) resources to be used in to deliver services and benefits Best value for water use (economic efficiency, cost-effectivity, and non-market methods as natural, human, and social capital)

2. Background of alternative practices and CE principles

Alternative practices in water management have been implemented to address climate change and urbanization pressures for a more sustainable urban water management (Adem Esmail and Suleiman, 2020). These practices can lead to multiple benefits and services, such as urban water balance restoration, multifunctional ecosystems, resource recovery, and water reuse. Similar to water reuse, energy and nutrient reuse could promote shifts at different spatial scales, ranging from households, to cities, to landscape levels (Hoffmann et al., 2020).

Challenges identified for the integration and management of water systems include comprehensively assessing the CE, reintroducing nature, and decentralizing infrastructures. In particular, an overall model establishing what needs to be measured and how to do this has been proposed, which designs a framework for a comprehensive CE assessment (Nika et al., 2020a, 2020b, 2020b). However, practical applications based on comprehensive CE assessments (that use various methodologies and indicators) may be difficult to report due to high levels of complexity (e.g., information flow, economic valuation, feedback loops, and sectoral interdependence) (Nika et al., 2020b).

Research on reintegrating nature into human-managed water systems has focused on the potential of implementing nature-based solutions (NBS) to address different water challenges (Nika et al., 2020a). NBS are defined as actions inspired and supported by nature that deliver

benefits (ecological, social, and economic) (Bauduceau et al., 2015). In urban water management, NBS address diverse issues, such as flood risks, droughts, stormwater management, and freshwater withdrawals, as well as challenges related to water pollution (e.g., phytoremediation). Various types of NBS for water management in peri-urban areas have been implemented, including wetland-related approaches (based on natural, constructed, and/or purpose-built wetlands), sustainable urban drainage systems (SUDS), and river parks (Ramírez-Agudelo et al., 2020).

Decentralized systems for water reuse with new technological elements, such as water reuse technologies (WRT), could promote changes at the micro-, meso-, and macro-level of water systems (Hoffmann et al., 2020). Elements of WRT include features that provide benefits through digitalization (such as wireless monitoring, membranes for reverse osmosis, and waste-to-value technologies) and that allow interventions to be embedded into the grid-dominated infrastructure (such as data monitoring, sensors, and smart controls) (Hoffmann et al., 2020). NBS and WRT as alternative water management practices may support the use of the CE paradigm in water systems (Hoffmann et al., 2020; Nika et al., 2020a).

At the strategic level, these alternative practices use a general rationalization principle in water resource use and recovery, and emphasize using new management logics, such as sensitive or hydraulic logic (Fuenfschilling and Truffer, 2014). For instance, a sensitive logic could be related to a socio-ecological approach to urban water management (e.g., by incorporating NBS), and a hydraulic logic could be related to a socio-technical approach (such as the efficiency and optimization objectives of WRT). The socio-ecological approach of NBS encourages multidimensional responses, including ecosystem services, risk management, and urban amenities, positioning NBS as a priority for urban sustainability in European policy (Bauduceau et al., 2015). In terms of ecosystem services, NBS are recognized to promote human well-being, of both physical and mental health (Raymond et al., 2017). The socio-technical approach of WRT is represented in a variety of environmental technologies and includes the smart tactic resolving specific technical challenges, while involving the users in “fit-to-purpose” strategies for water demand management (Domènech et al., 2015).

CE could enable shifts in water systems by following three principles: 1) regenerate natural capital, 2) keep resources in use, and 3) design out waste externalities (Arup and Ellen MacArthur, 2018; Nika et al., 2020a, 2020b). The ‘CE concept’ functions as a connecting link, ensuring functional environmental flows and stocks, closing resource loops, and increasing the economic efficiency of waste reduction in water systems (Nika et al., 2020a, 2020b, 2020b). The literature on CE in water systems describes that the CE principles may be associated with specific actions and examples of potential circularity features, thereby promoting shifts in the water systems, as these individual features are interconnected and contribute to SUWM.

Regenerating natural capital aims to prevent pollution and restore natural capital, and thereby ensure functional environmental flows and stocks. Recommended actions supporting this principle are related to natural capital preservation and enhancement, and to processes in which human interactions/use cause the minimum disruption to natural water systems (Arup and Ellen MacArthur, 2018; Nika et al., 2020a, 2020b). Potential circularity features include ecosystem health support and improving the quality of discharge effluents (e.g., improving biodiversity, greening and cooling properties, water quality of the effluents, waterways, and urban landscapes) (Jazbec et al., 2020; Nika et al., 2020a, 2020b). This principle endorses the regeneration of the natural and urban environments to contribute to SUWM.

Keeping resources in use aims to maximize water use by i) keeping it in the landscape, ii) close resource loops, and iii) preserve its value as long as possible through recovery, reuse, and up-/recycling. Benefits are derived from the value generated at the water systems’ interfaces with other systems, as well as by optimizing resource yields within water

systems and management (Arup and Ellen MacArthur, 2018; Nika et al., 2020a, 2020b). Potential circularity features include reducing water use and optimizing resources, which are exemplified by reducing use in water consumption and non-consumption, streamflow augmentation by returning wastewater to waterways, maximizing environmental flows, and best use when operating water systems with other systems (which should optimize water, minerals, chemicals, and energy) (Nika et al., 2020a, 2020b, 2020c). To contribute to SUWM, this principle endorses synergies among urban systems that better support livability and the local community, and thus the social dimensions of livability (Arup and Ellen MacArthur, 2018; Jazbec et al., 2020).

Designing out (waste) externalities targets environmental and social impacts, as well as the economic efficiency of waste reduction. The recommended actions address i) the negative impact on both environmental and social dimensions, and ii) how to improve the economic dimension by resource efficiency in terms of the right assessment of the amounts and the value of resources. Potential circularity features include risk management, efficiency of resource use in services and benefits, and assessment for best value of water use. Risk management—for example, through stormwater attenuation—contributes to reduced discharge in the environment, reduced atmospheric emissions, and lower social exposure. Actions that target resource efficiency aim to use the least amount of (fresh) resources to deliver services and benefits, and to establish best value for water use of not only economic efficiency and cost-effectiveness but also through non-market methods (including assessments in terms of natural, human, and social capital) (Arup and Ellen MacArthur, 2018; Jazbec et al., 2020; Nika et al., 2020a, 2020b). To contribute to SUWM, this principle endorses the correct valuation of the waste reduction in terms of social and environmental impacts.

To summarize, each CE principle can be associated with specific actions, potential circularity features, and examples (Table 1). Moreover, these analytical categories are interconnected; when viewed as a set, they can give information about the incremental shifts that contribute to system integration and urban water cycle management towards SUWM.

3. Materials and methods

This research was conducted using a case study of water reuse experiences through NBS and WRT, aiming to present a detailed analysis of how alternative practices in urban water management contribute to transformative changes towards SUWM. For illustrating advances through NBS and WRT implementation in a specific urban context, the CE principles were used as analytical categories to examine each category as a linear-analytical approach (Van Der Blonk, 2016). This analysis identifies the CE principles in terms of evidence for related actions, and potential circularity features; however, a limitation is the increased complexity of findings due to the interconnectedness of these actions.

3.1. Study area

The study focused on the context of the Besòs river in the Barcelona metropolitan area (*Àrea Metropolitana de Barcelona*; AMB). It presents an urban and peri-urban context facing water challenges related to water quality, caused by industrial pollution, as well as unpredictable water quantities (e.g., after scarcity or flooding). Water challenges have been linked to freshwater withdrawals and reduced river flow in the river Besòs area, as well as to flooding due to torrential rains and inundating risks in underground infrastructures (Pol Masjoan et al., 1999; Tubau et al., 2017). At the end of the 20th century, the main water challenges for the Besòs river were mitigating the poor water quality (due to heavy industrial pollution) and the relatively high risks of flooding (Santassusagna Riu, 2019).

To address these issues and prevent further pollution, a major river restoration project sponsored mainly by European funds began in 1996, to improve the riverbed's environmental conditions, including its

hydrology as a natural system, and to allow recreational use of the river banks (Pol Masjoan et al., 1999; Santassusagna Riu, 2019). By 2006, NBS were integrated into a riverside park and constructed wetlands (2003), resulting in a significant investment in the Besòs river and the AMB (Martín-Vide, 2015); it also is a pilot for WRT (Fig. 2).

3.2. Data collection

This study is based on a mixed approach of quantitative and qualitative data, using data collected through interviews, complemented with field observations, and a desk review of secondary sources. Between 2019 and 2020, four in-depth interviews were conducted to acquire perspectives from different stakeholders, who are either directly or indirectly involved with the alternative practices: i) in academia, a person involved in the development of the WRT; ii) in government, a member of the local consortium involved in NBS and WRT; iii) for civic society, an environmental activist and resident of the area; and iv) in industry, a person involved with the area's urban metabolic infrastructure. Field observations were conducted during multiple visits between 2019 and 2021 to gather the infrastructure's various spatial aspects.

3.3. Data analysis

Analysis was for the interaction of two key themes: i) the CE principles and ii) the historical context of implementation of alternative practices (Table 2). The CE principles are used as analytical categories to build evidence for related actions and potential circularity features based on the framework presented in the background section. Results were validated by triangulation, with the various data (such as quantitative data on water quality) integrated; the themes identified during the interview analyses (including quotes), accounts from observations, and established ideas in the literature are presented. This style of reporting is intended to highlight that examining the support of the CE principles also jointly addressed the question of how alternative practices contribute to SUWM.

The topics aiding the analyses of natural capital regeneration principle were natural capital preservation and enhancement and pollution reduction. Topics illustrating 'how to keep resources in use' included maximizing water use and maintaining resource value. The analysis of 'designing out (waste) externalities' was supported by the topics of tackling environmental and social impacts, as well as targeting efficiency of resources.

Regenerating natural capital is presented as the advances in the support of the ecosystem's health towards capital preservation and enhancement of nature through the NBS using data related to biodiversity monitoring, including the IBMWP index from an academic observer (e.g., the Barcelonari project; Universitat de Barcelona, 2021). Actions oriented to minimizing disruption from human interactions and to improving the quality of the effluent discharge are related to water quality, using NBS for the Besòs river and potentially WRT for the aquifer (See details on data and references in the Appendix).

4. Results and discussion: How do alternative practices contribute to SUWM?

For the case study of the Besòs river area, alternative practices were implemented through several actions and (potential) circular features along the three CE principles: biodiversity and water quality improvements, through NBS supporting natural capital regeneration (4.1); water reuse for streamflow augmentation and multi-functional infrastructure, which keep resources in use (4.2); and management of flooding risks and a potential fit-to-purpose strategy for avoiding waste externalities (4.3).

4.1. Regeneration of natural capital

The Besòs river area aims to prevent pollution and restore natural

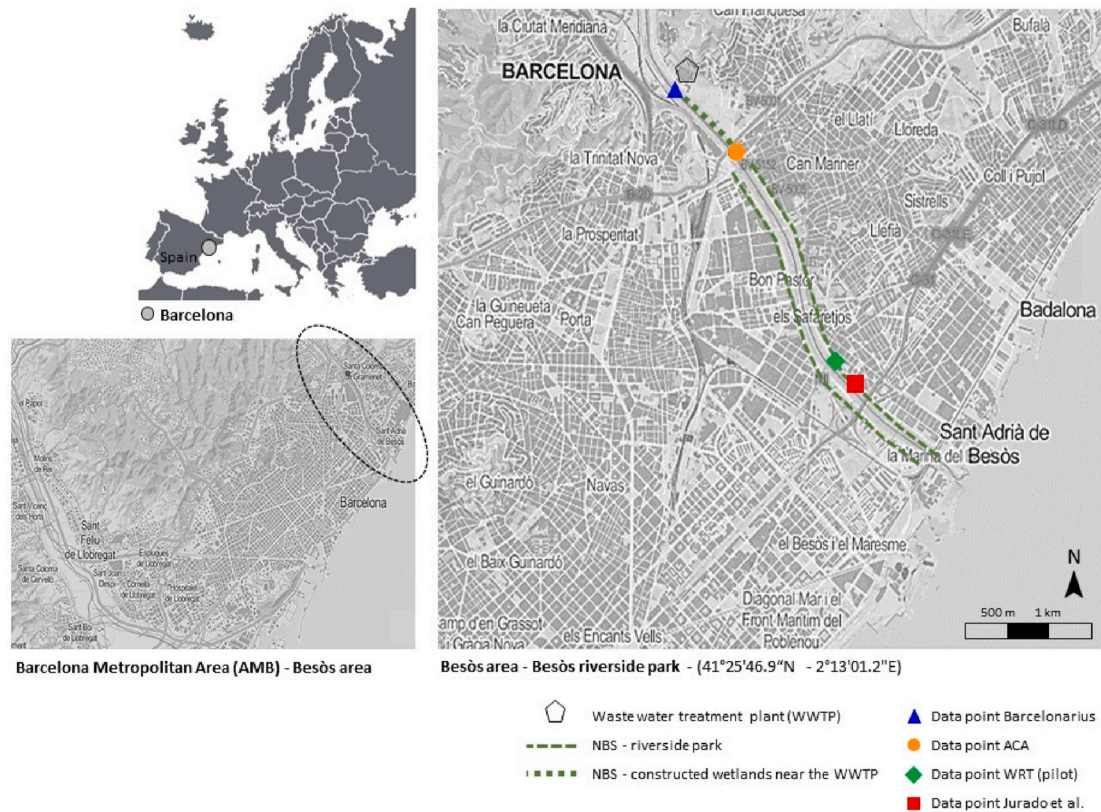


Fig. 2. Besòs river area: location of the case study, alternative practices, and observation points.

Table 2
Data analysis and integration of data through the case study.

Key themes	Data collection		Data sources			Input for alternative practices	
	Topics from the literature=	Aspects searched	Desk review	Interviews	Field observations – (NBS)	NBS	WRT
Alternative practices	Study area - Historical background implementation process	Context of the case study	X		X	X	X
		Conditions for its emergence	X	X		X	X
		Outcomes	X	X	X	X	X
CE - SUWM	Natural capital preservation and enhancement	Ecosystems health - Biodiversity	X		X	X	N.A.
		Greening and cooling properties				No information	
	Minimizing pollution	Water quality – nutrients presence, regulatory limits for reuse purposes	X			X	X
	Maximizing the use of water	Water quantity - Streamflow	X	X	X		
	Maintenance of resources value	Nutrients optimization				No information	No information
	Tackling environmental and social impacts	Water challenges - flooding risks	X	X	X	X	X
Targeting efficiency of resources	Best value for water use				No information	No information	

capital, to ensure functional environmental flows and stocks; this is developed through two actions: 1) preserve and enhance natural capital, and 2) minimize disruption due to human interactions with and use of natural water systems.

Environmental degradation and pollution of the Besòs river area was first addressed with an alternative practice for water reuse in a restoration project that included NBS (1996–2006). NBS were implemented by i) creating a 22-ha, 9-km-long riverside park; and ii) constructing wetlands around the Montcada i Reixac wastewater treatment plant (WWTP) in 2003. These solutions not only promote biodiversity but also support the ecosystem health, improve the water quality of the Besòs river and aquifer, and promote improvement of the discharged effluents.

Various biological indicators were used to measure biodiversity,

such as the invertebrate benthic fauna index IBMWP (Fig. 3), for which the Catalan Water Agency (ACA, *Agència Catalana de l'Aigua*) provided data that showed an overall increase in biodiversity in the area, from 1996 to 2017 (from 0 in 1996, to 3 in 1999, to 48 in 2017). Both NBS programs contributed to this increase, as evidenced by the positive results for the biological quality measured by the Barcelonarius project (Universitat de Barcelona, 2021) and the Water Agency data (ACA, *Agència Catalana de l'Aigua*). Nevertheless, it has been argued that if forest quality is considered with the overall ecological status, the ecological state of the lower Besòs river area remains negative (Fortuño et al., 2020).

Nitrate concentrations in the river were less than 25 mg/L until 2013, which is the accepted limit set by the river quality directive as

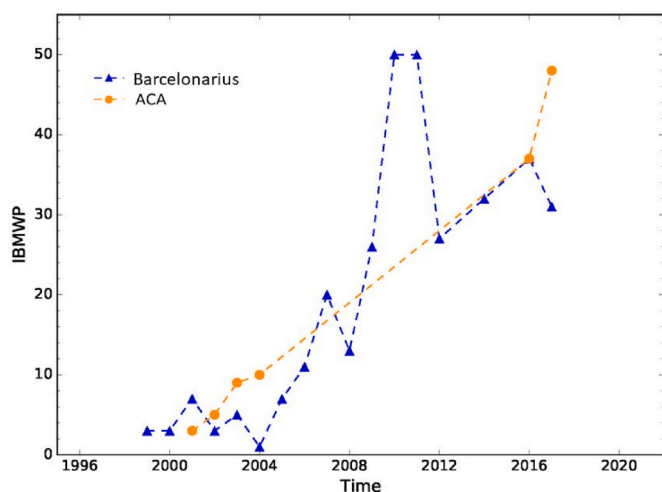


Fig. 3. Biodiversity index IBMWP - Besòs river 1999–2017.

good/moderate (Fig. 4). Since 2014, seasonal fluctuations have increased these nitrate levels, even though the levels have remained below the accepted limit of 50 mg/L required by drinking water regulation and the river’s ecological flow maintenance. These results seem to show that using the NBS wetland in the river (since 2003) has not decreased nitrate concentrations.

The phosphate concentrations in the river exceeded the established limits until 2015. However, since 2017, it has remained below the 2 mg/L limit established by the Barcelona irrigation water parameter (Fig. 5). This decrease in phosphate concentrations could be due to an improvement in the treatment at the WWTP, which uses chemical reagents that favor the phosphate precipitation.

Disturbingly, the ammonium concentrations have fluctuated between 30 mg/L and 5 mg/L from 1998 to 2009 (Fig. 6). Since 2008, it has ranged between 20 mg/L and 1 mg/L. Currently, the upper established limit for ammonium is 5 mg/L, established by the Barcelona irrigation water parameter, and the lower limit is 1 mg/L for ecological flow maintenance. It is important to consider that, depending on the pH,

part of the ammonium can be transformed to ammonia, which is toxic to certain species, including fish.

The constructed wetlands (NBS) have served as an integrated solution for natural purification to the WWTP by reusing some of the treated water on cultivated land, thereby maintaining the existing vegetation of the Besòs river reedbeds. NBS have served for enhancing and preserving the river’s water quality. The effluent quality has improved because of the constructed wetlands, which assist in purifying the used waters. However, nitrate and ammonium concentrations are insufficiently assimilated, both in the river and in the aquifer; this reflects the connection between the two water bodies. Environmental preservation of groundwater-dependent ecosystems, such as riparian areas and wetlands, has been critical for maintaining nitrogen assimilation rates (Mas-Pla and Menció, 2019).

In contrast, we could determine (despite the scarcity of data on nutrient concentrations in the aquifer) that, until 2011, nitrate concentrations of the aquifer were less than 10 mg/L (Fig. 7). This level is very low compared to levels in aquifers affected by agriculture and livestock activities. After 2011, it remained between 10 and 25 mg/L, which is also lower than the levels found in the most contaminated areas of Catalonia (Mas-Pla and Menció, 2019).

No data on phosphates in the aquifers were identified, which could also indicate that its concentration was below the detection limit.

Until 2008, ammonium levels in the aquifer exceeded 5 mg/L; from 2010 to 2014, they ranged from 2 to 4 mg/L (Fig. 8). These values pose a problem for groundwater reuse, as its concentration must be less than 1 mg/L, except for irrigation purposes. To achieve this limit, osmosis membrane technology (among others) should be considered.

Implementing the WRT reduced nitrates and ammonium to allowed concentrations, confirming its capacity to improve the reuse of water pumped from the aquifer. Despite this, it is still unclear how best to minimize disruption to natural water systems caused by human interactions and use, as ammonium concentrations in the river and aquifer exceed the maximum limit of 5 mg/L. Progress in complementary treatments, such as WRT based on reverse osmosis, may increase the potential to reduce ammonium concentrations.

To summarize, restoration of the Besòs river has been documented as advances towards natural capital preservation and enhancement. The

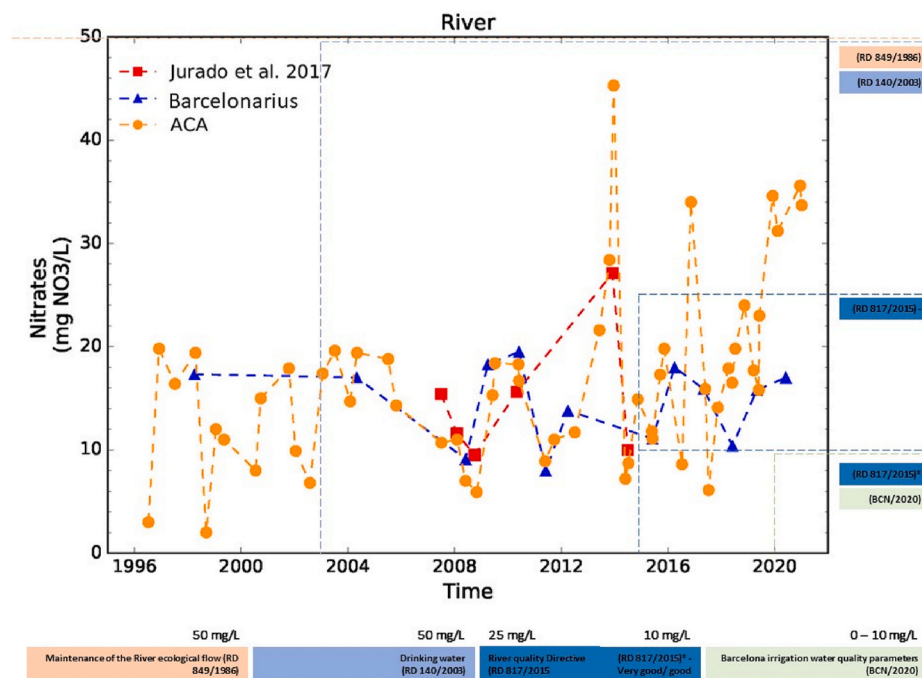


Fig. 4. Nitrate concentrations (mg/L) in the Besòs river 1996–2021.

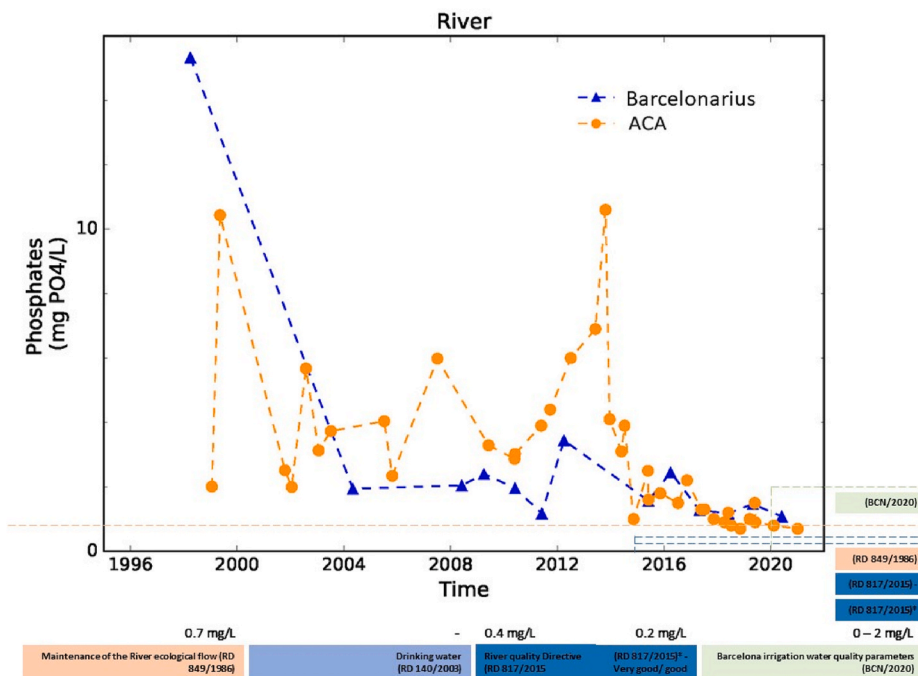


Fig. 5. Phosphate concentrations (mg/L) in the Besòs river 1999–2021.

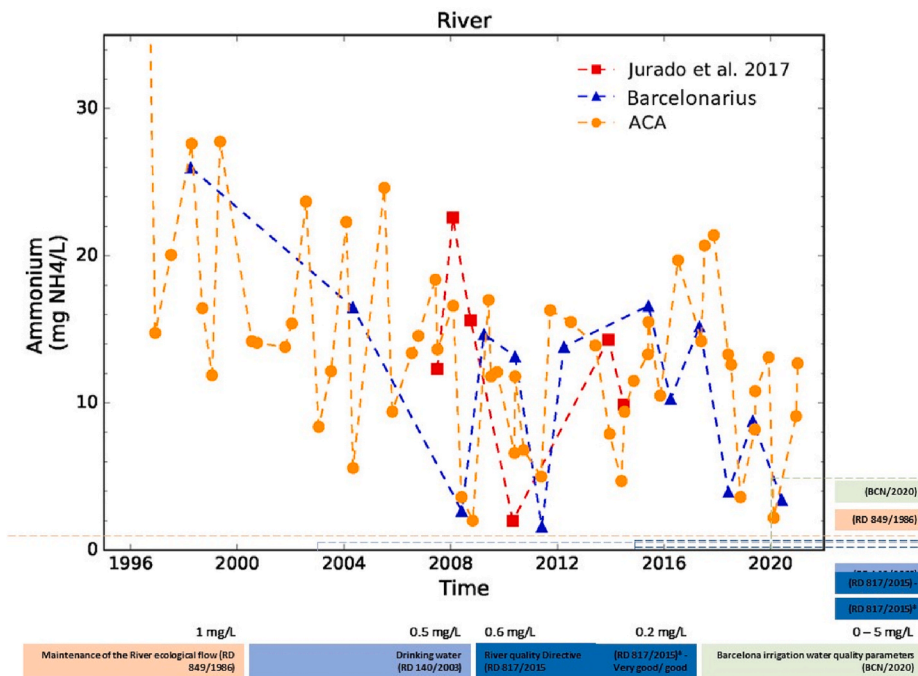


Fig. 6. Ammonium concentrations (mg/L) in the Besòs river 1996–2021.

availability of data from water quality analyses help to monitor the quality of the effluent discharge. At present, according to the AMB, the wetlands currently act like a tertiary treatment of the WWTP (AMB, 2021). The Besòs river area is considered a strategic area for the metropolitan water cycle, as it is connected to the green and blue metropolitan infrastructure goals of renaturalization (AMB, 2021).

These findings demonstrate that the described actions are linked as a sequential process: the circularity features initially prevented pollution, then natural capital was restored, and thus functional environmental flows and stocks currently guarantee the regeneration of the natural

capital and the urban environment of the Besòs river area.

4.2. Keeping resources in use

Keeping water in the landscape supports the purpose of maximizing water use, which highlights the benefits from the value generated in the interface of water systems with other systems. The analysis identified that water reuse served as an input for streamflow augmentation by returning wastewater to the Besòs river (Fig. 9). The data present descriptions of the effects of streamflow augmentation that distinguish the

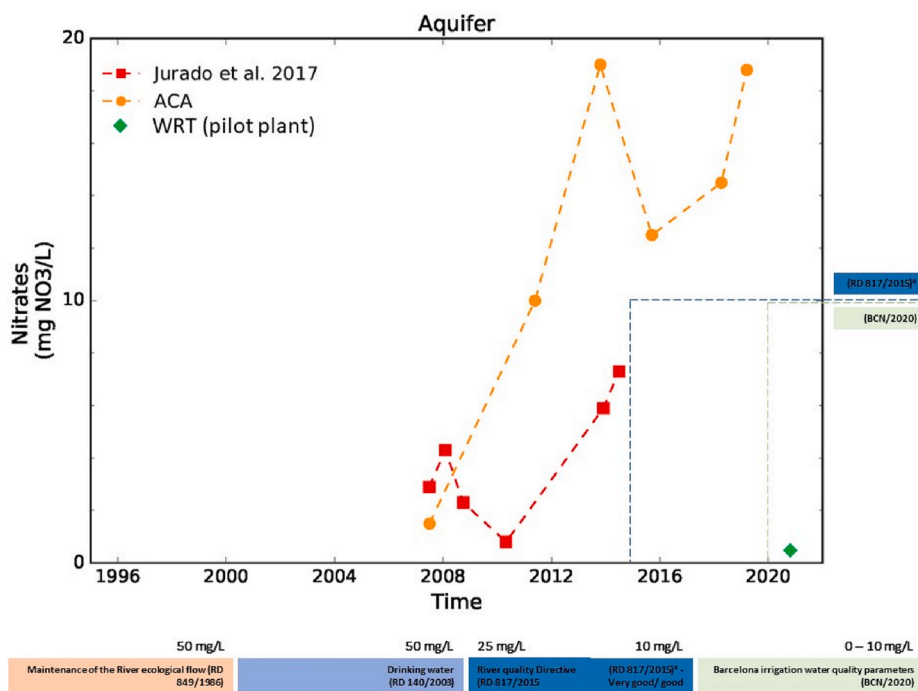


Fig. 7. Nitrate concentrations (mg/L) in the Besòs aquifer 2007–2021.

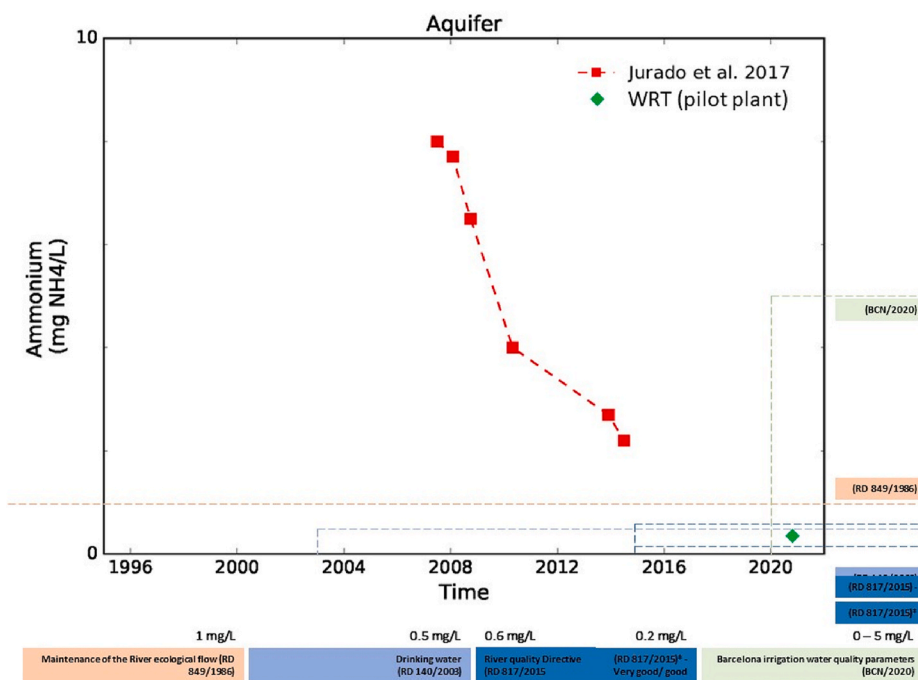


Fig. 8. Ammonium concentrations (mg/L) in the Besòs aquifer 2007–2014 measured with WRT 2020.

benefits obtained as NBS, such as the constructed wetlands and the riverside park along the Besòs River, and the potential benefits of WRT for the aquifer.

This case study presents how a challenge related to reduced river flow has improved significantly after the goal of an integrated river basin management was established in 1995, incorporating 25 WWTPs in the Besòs basin area (1038 km²) (Boada et al., 2018). For instance, WWTPs in the Besòs area currently treat an average of 259.37 hm³ of wastewater per year, which is nearly half of the AMB total volume (532.29 hm³), and this ultimately flows into the Mediterranean Sea. The

Montcada i Reixac WWTP can treat 72 million liters per day, equivalent to the water consumption of 360,000 inhabitants and associated economic activities (AMB, 2021). NBS keeps resources in use, as it receives 1 hm³/year of regenerated waters from the WWTP through the constructed wetlands. As it was mentioned by the government interviewee: “the wetlands that were built ... are taking advantage of the water that comes out of the WWTP, to provide a biological treatment, which shows that a natural solution ... can improve the quality of the area that goes in the river”. This integration has benefited the WWTP as a key intervention space for preserving water as a raw material (Nika et al., 2020a), the wastewater



Fig. 9. NBS - Besòs river park in the Barcelona metropolitan area.

quality, the Besòs river, and (indirectly) the aquifer. This fact has improved the hydraulic capacity, which is significant in the overall urban water management, as this represents a substantial physical change for the area's landscape.

The riverside park has benefited from the streamflow augmentation, allowing recreational use of the river's banks and fostering synergy between urban public space and urban amenities (Bauduceau et al., 2015). As an added value to urban water systems, streamflow augmentation is based on the interface of a natural process with the WWTP and integrated as a hybrid scheme (Hoffmann et al., 2020). This NBS has served not only for recreational purposes by integrating the urban waterfront with its natural areas, but also to create a public space for contemplation and mobility along the river. The landscape's high multifunctionality results in nearly million visits per year and delivers social benefits, such as physical health (Vert et al., 2019).

For the aquifer, overexploitation was identified as part of a diagnosis of the main environmental effects on the Besòs area in the 1990s (Santusagna Riu, 2019). According to the entity responsible for integrated water cycle management (Aigües de Barcelona, the Barcelona water provider), the aquifer provides 6–10 hm³/year of the 283 hm³ required for the metropolitan area. This resource involves the removal of excessive salts and organic matter, which the Besòs water treatment plant accomplishes via nanofiltration and reverse osmosis (Aigües de Barcelona, 2021). In the case of the WRT, according to the academic interviewee: “the river is the major source of groundwater origin and that interaction of the river, with all the contributions of the treated wastewater discharges from the entire Besòs basin. The ‘Pect Littoral Besòs’ (RIS3 project) is the interface between groundwater and the river.”

These findings demonstrate that the described actions are linked as a synergy, and that by working in an integrated manner, the social dimensions of livability have benefited: resource loops were kept closed to maximize water use; as a result, resources are kept in use and actively preserve the value generated at the interface of water systems with other urban systems (i.e. public space, mobility, recreation, and health).

4.3. Designing out (waste) externalities

Analyses of designing out externality mainly focused on two actions:

i) targeting the negative impact for the environmental and social dimensions, and ii) improving the efficiency of resources (value and amount) for their correct valuation. The analysis traced risk management and resource efficiency as indications of progress toward reduced levels of discharge to the environment and reduced social exposure, as well as best value for water use and amounts of (fresh) resources. Data present descriptions that distinguish the deployment of NBS and WRT, because there are no suggestions on interrelated effects for the reduction of externalities.

NBS are the wide-ranging response to flooding risks, which have been addressed by constructed wetlands and the riverside park along the Besòs River. The NBS implementation considered the torrential profile of the river and the management of flooding risk after the 1962 flood, of 2345 m³/s, to be the last 500-year flood (Tort-Donada et al., 2020). To illustrate this point, the civic interviewee pointed out the relevance of water reuse through NBS for addressing the negative social and environmental impacts as “... the Besòs was a rainbow-colored sewer. And they (public authorities) said: No, you can't throw it down the drain. So, what are your options? You construct a sewage treatment plant; then, do you discharge treated sewage into the river? Not at all! You reuse the water because it has already been cleaned. That is to internalize, when you practice it, the entire degradation process that results in your productive process; you save as much money as possible on clean industry systems, recycling systems, reuse systems, and purification systems ...”. Previous research has claimed that resource efficiency based on NBS should be given more emphasis; for instance, risk management costs have been avoided because of the green corridor intervention and particularly along the river banks (Barcelona, 2013).

Underground urban infrastructures, such as parking lots and subways, faced flooding risks due to rising levels of aquifer groundwater (Tubau et al., 2017). As the academic interviewee described, this was addressed as isolated actions for technologies development, in which the groundwater potentials were based on the amounts of resources used, defined as the available resources volume (water quantity): “In the 1970s the industry left, and stopped the (need for) consuming water, so the water table caused flooding in the parking lots that were built, ...to avoid flooding of these parking lots, years ago the UPC (academy) installed an automatic pumping system, of about 300 or 400 L/S, or 6 to 10 hm³/year” This is consistent with the city's overall concern about groundwater

resources, as Barcelona was a pioneer in the development of a secondary distribution network for phreatic water (Tubau et al., 2017).

Besides water availability, a shift for a fit-to-purpose water is justified by the potential demand and supply coupling. The WRT emerged to achieve this purpose within the *Pect Littoral Besòs* project (2017–2021), which is based on a quadruple helix consortium of a regional innovation strategy based on smart specialization (RIS3) for urban sustainability research (<https://www.besosostenible.cat/>). In fact, the WRT has been developed for monitoring river and coastal water quality, to recycle these resources and for exploring more sustainable uses: “Currently, less than 1% is used for irrigation and 99% goes to the sewer system ... So, the initiative of this project (PECT) was to give a more sustainable use of these groundwaters.”

If supply is classified by water qualities, potential new demand can be identified based on how user consumption patterns and requirements can be coupled to specific use purposes, which reduces costs and unnecessary treatments, and thus designs out externalities. However, the academic interviewee described this process of coupling demand and supply as a challenge that depends on the economic activities settled in the area: “There isn’t much industry left here, it’s bad ... We are making an inventory ... and then we could find users, but on a smaller scale.” The area’s de-industrialization reduced demand for water resources, raising the question of who might benefit from the use of groundwater. As the development of the fit-to-purpose strategy is justified by the merge of demand and supply, potential long-term uses could be related to the Besòs river streamflow (closing the loop as *interface between groundwater and the river*) and the urban metabolic infrastructure, as described by the industry interviewee: “We (urban metabolic infrastructure) have gone from being a peripheral industrial area of extra-radius to urban fabric ... we are part of a city management service ... that maybe one day we will move out from 2 km from the sea, but at the moment it’s not viable.”

These findings highlight the apparent lack of an integrated methodology for (waste) externalities in the design-out process and the need for a perspective on the nexus among water systems and urban development. The actions and circularity examples for the river demonstrate how it is related to flooding risk and management, with NBS recognized for reducing externalities and avoiding costs (i.e. economic efficiency, cost-effectiveness). However, there is still a valuation gap that includes non-market methods, such as natural capital, human capital, and social capital. For the aquifer, our analysis shows isolated actions and examples of circularity in technological solutions that have improved resource efficiency in the short term. As a result, there is an opportunity to better target negative environmental and social impacts, as well as waste reduction efficiency, to support a correct valuation of designing out externalities.

5. Conclusions

In this study, we identified shifts toward SUWM supported by alternative practices. For this, we developed a framework of an interconnected set of analytical categories based on literature of CE principles and water systems, which was used in a case study. This research combines different information sources to provide a general representation of the Besòs river case, focusing on the role played by NBS and WRT in a two-decade process of interplay with the urban water system and its context-specific dynamics. This study contributes to the operationalization of CE by providing an integrated understanding of alternative practices, their uses, the circularity of features and actions, and their implementation and outcome for SUWM.

Our results show alternative practices regenerated natural capital through NBS, thus supporting ecosystem health and preserving and enhancing biodiversity and water quality; overall, NBS and WRT aim to prevent pollution and reduce human disruption. The shifts promoted by these actions and circularity features are linked as a sequential process. NBS has been key for repurposing wastewater for streamflow augmentation, which keeps resources in use, while promoting synergies with the

public space, for mobility, recreation, and improved health. The shifts promoted by these actions and circularity features work as a synergy. NBS and WRT have been integrated to allow both risk management and fit-to-purpose strategies; using WRT could help to increase the marginal potential and avoid waste of resources. However, these actions and circularity features need an integrated methodology to address the nexus between water systems and urban development, to promote designing out waste externalities.

As these analytical categories are interconnected, their contributions to SUWM reveal how actions and circularity features endorse flexibility and cross-sectoral collaborations. Specifically, flexibility and cross-sectoral collaborations are supported by: i) active monitoring that captures the sequential process of change; ii) communication about the benefits to the lay citizens that emphasizes the synergy among urban systems; and iii) improving accountability of both the market and non-market values, as a good methodology related to reducing externalities.

These findings imply that both the socio-ecological approach of NBS and the socio-technical approach of WRT contribute to integrating and managing water systems in complementary ways. Further, incremental shifts at the micro-level contributed to a local system integration and more sustainable urban water cycle management. This is important, as alternative practices can dynamically reformulate the problem at the urban systems intersections, allowing the context-specific challenges where these practices take place to be addressed. For instance, the initial input for NBS was to avoid resource degradation in the river, and for WTR, to avoid resource waste in the aquifer. In contrast, the current challenges are related to production and consumption patterns of users, which this in turn depends on the nexus with the activities and uses of urban land, regardless of the technology.

Finally, integrating and managing water systems will require higher levels of collaboration to support a cross-sectoral strategy and flexibility; such a joint effort will be able to address this challenge of urban systems intersections not only in the short term, but also in the long term. Further research could develop a similar analysis, as these findings are limited to one local case study, and additional evidence could better demonstrate the nature of the links used for the integration and management of alternative practices, water systems, and urban development.

CRedit authorship contribution statement

Nancy Andrea Ramírez-Agudelo: Conceptualization, Methodology, Investigation, Writing – review & editing. **Joan de Pablo:** Methodology, Investigation, Writing – review & editing, Funding acquisition. **Elisabet Roca:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

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