

Review

The role of digital technologies for circular economy in the water sector

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Circular economy offers a promising pathway to address the global water crisis, yet its application in the water sector remains fragmented. Over the past two years, rapid advances in digital technologies have begun to reshape circular water systems. This paper synthesises recent literature on how digital technologies could enable circularity across water systems. We propose a consolidated 7Rs framework tailored to the water sector under three areas: (i) minimising water use and waste (*Reduce*), (ii) optimising the value of water and wastewater (*Redistribute, Reuse, Recycle and Recover*) and (iii) maximising water resource generation (*Restore, Regenerate*). In particular, we highlight *Regenerate* as an emerging strategy focused on upgrading water quality for high-value applications. Our review shows that these circular strategies are rarely enabled by single technologies alone, but by integrated digital systems and their underlying functions. We identify ten key digital functions for water circularity and find that applications are most advanced in *Reduce*, *Recycle* and *Recover*, with *Reduce* representing a particularly accessible, high-impact strategy for practitioners. We also argue that digital technologies are no longer limited to efficiency improvements, but increasingly support system-level strategies for demand reduction, intelligent water redistribution, large-scale reuse and recycling. The review concludes by identifying key technological, economic and institutional conditions for adopting digital circular water systems and outlines priorities for future research.

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Introduction

Global water systems are under unprecedented pressure from population growth, rapid urbanisation, rising demand and accelerating climate change. Water scarcity is no longer confined to arid regions; even high-income countries with advanced infrastructure face substantial inefficiencies [1]. In parts of Europe, for example, around 40–60% of water is lost before reaching end users due to ageing infrastructure, leakage and inappropriate management [2]. These losses occur across industrial, agricultural and municipal uses, exposing the limitations of the current prevailing linear model in the water sector [3].

Addressing the global water crisis requires an urgent transition towards a circular economy (CE) in the water sector. Unlike many materials, water has a unique property: its quality can be degraded, restored and in some cases upgraded to higher standards through treatment. This property creates exceptional opportunities for repeated and potentially high-value use of water across sectors.

Recent research has increasingly highlighted the role of Industry 4.0 digital technologies — particularly the Internet of Things (IoT), Artificial Intelligence (AI), digital twins and automation — in enabling circular water systems [4–8]. Real-time sensing and AI allow water systems to move beyond reactive and descriptive functions towards predictive and preventive management [9,10]. Recent studies show that digital tools can reduce water losses through leak detection and predictive maintenance [5,11,12], optimise agricultural irrigation and industrial water use [13–15], improve wastewater treatment efficiency [16,17], and enhance the recovery of energy and nutrients from wastewater [14,18]. Digital platforms can also coordinate cross-sectoral reuse and align supply and demand for reclaimed water and recovered resources [5,6,19].

Despite this progress, research on digital CE in the water sector remains fragmented. Existing studies often focus on individual technologies or isolated R-strategies — particularly wastewater treatment or recovery — while overlooking the system-level potential of scaling water reuse and recycle. Moreover, CE frameworks applied to water vary widely — from 5Rs to 8Rs [20–24] — using inconsistent terminology and overlapping definitions, making it difficult to clarify the boundaries between R-strategies. As a result, the water sector lacks a coherent framework that links circular strategies with digital capabilities [23,25].

This paper addresses this gap by reviewing literature published between 2020 and 2025, with a focus on the past two years. The paper adopts a combination of systematic literature review and snowballing methods. The review process (e.g. search strings, databases and selection criteria) is presented in Appendix Figure A1. The initial search identified 1119 articles. After deduplication and screening, 40 articles were selected for snowballing. Forward and backward citation tracking expanded this to 63 articles for full-text analysis, of which 58 form the basis of this review.

Building on this literature, we propose a consolidated 7Rs CE framework tailored to the water sector, organised under three areas: (i) minimising water use and waste (*Reduce*), (ii) optimising the value of water and wastewater (*Redistribute*, *Reuse*, *Recycle* and *Recover*) and (iii) maximising water resource generation (*Restore*, *Regenerate*). The distribution of papers across these R-strategies is presented in Appendix Table A1. Using this framework, we propose that digital technologies could enhance circular strategies in the water sector through ten key digital functions.

How can digital technologies enhance circular water systems

Circular water systems are implemented through various R-strategies, yet existing frameworks vary in scope and terminology. Recent frameworks range from 5Rs to 8Rs [20–24], reflecting growing recognition of circularity as a system-level strategy but also resulting in conceptual inconsistency. For example, some studies define *Recycle* as reuse of treated water within the original loop and *Reclaim* as reuse outside the loop [20,24], whereas others use *Reclaim* primarily as pollutant removal during treatment [21,23]. In contrast, terms such as *Reclaim*, *Removal*, *Recover* and *Recycle* are sometimes used interchangeably [22,23], further obscuring conceptual boundaries.

To address this, we conducted a critical comparative analysis of existing R frameworks proposed by different authors, guided by the following questions: (i) how each R is defined; (ii) similarities and differences across frameworks; (iii) the extent to which these frameworks cover circularity in the water sector and what is missing; (iv) areas of overlap between Rs; and (v) whether certain Rs could be merged or further differentiated. Based on this analysis, we consolidate the findings into seven core R-strategies, organised under three objectives central to CE in the water sector. Table 1 provides definitions of the 7Rs and representative examples. This 7R framework provides a coherent structure that clarifies R-strategy boundaries and enables systematic analysis of digital contributions.

The water lifecycle spans water generation, storage, distribution, use across industrial, agricultural and

municipal systems, and wastewater collection and treatment. Figure 1 illustrates how digital technologies could enhance the proposed 7Rs across the water life-cycle.

Minimising water use and waste: reduce

Reduce strategy refers to decreasing freshwater use and preventing wastewater generation. It is the highest priority in circular water systems, as it directly lowers water consumption [24] and avoids waste at source [23], delivering immediate environmental and economic benefits.

Digital technologies enhance this strategy by integrating monitoring, predictive analytics and automated control across agricultural, industrial and municipal water systems. In agriculture, where around 69% of global freshwater is used for irrigation [14], digital technologies can massively reduce water use by optimising irrigation [15,26,37]. Studies show that combining IoT, digital twins and AI can integrate real-time data on soil, weather and crops to optimise irrigation scheduling [38,39]. Smart irrigation controllers using predictive models demonstrated 15–40% water savings compared to traditional practices [27]. In industrial and urban water networks, digital technologies also play a critical role. Real-time monitoring of water flow and AI-based anomaly detection are increasingly used to identify leaks, predict pipe failures and prioritise maintenance [5,12,40]. These approaches reduce non-revenue water and enable faster responses to system disruptions [4,32].

Optimising value of water: redistribute, reuse, recycle and recover

Redistribute, *Reuse*, *Recycle* and *Recover* strategies focus on maximising the value extracted from water once it has entered the system. These strategies are particularly important in growing water scarcity.

Redistribute strategy refers to the allocation of water resources based on the supply and demand across regions and time periods. Redistribution enables water of appropriate quality to be allocated from relatively abundant sources to water-stressed regions, sectors or time periods [29,31]. The principle is to prioritise high-quality water for potable supply and allocate lower-grade water to industrial or agricultural applications [41]. Building such a redistribution is highly complex. Digital technologies, such as digital twin and AI, could optimise this process through supply-demand monitoring and predictive allocation models, while improving reliability and reducing engineering risks [42]. Digital platforms also enhance transparency and inclusiveness [30] by enabling controlled data sharing across institutions [5,6].

Reuse and *Recycle* strategies are central to circular water systems but are often highly overlapping in the literature

Table 1

7R framework for circular economy in the water sector: definitions and examples.

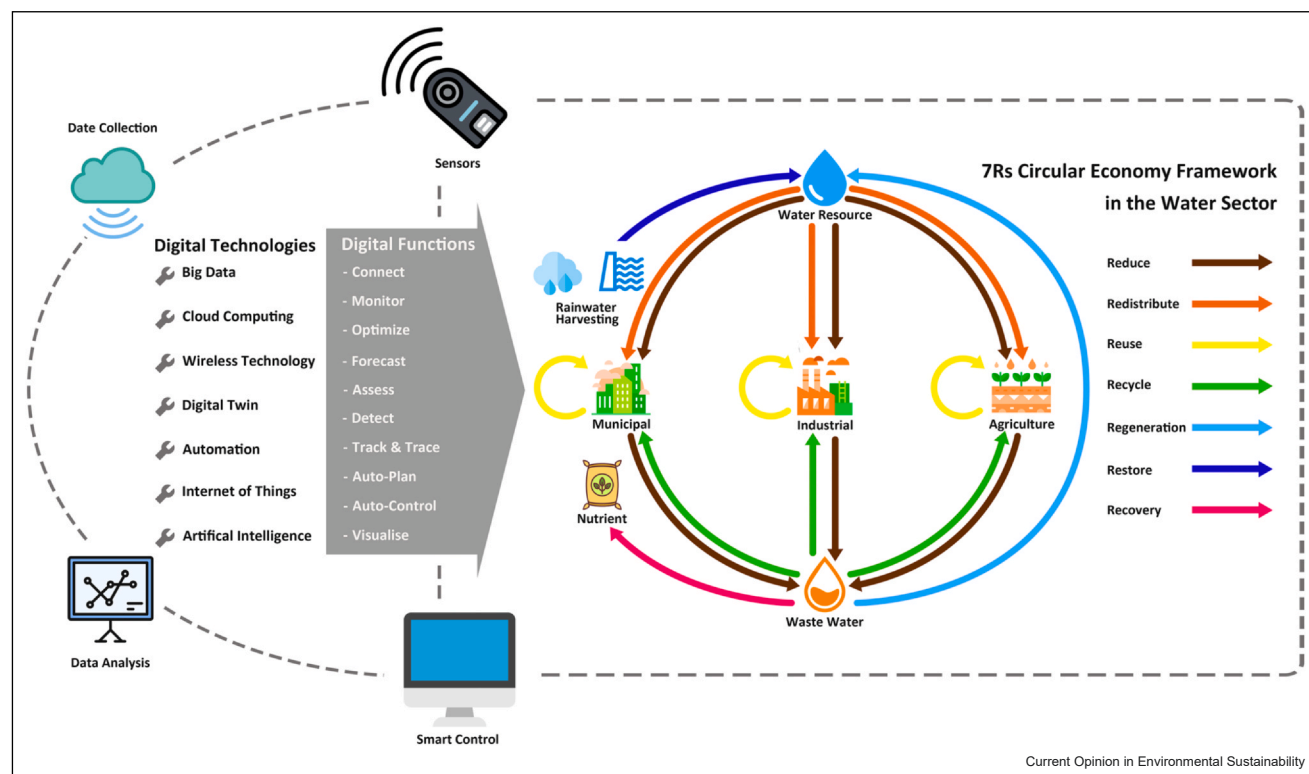
	R strategy	Our definition	Examples in literature (may use different terms)
<i>Minimising water use and waste</i>	<i>Reduce</i>	Decreasing freshwater use and preventing wastewater generation	<ul style="list-style-type: none"> • Applied IoT and digital twin to create a smart irrigation system that optimises agricultural water use in real-time [14,26] • Used hydraulic simulation with smart irrigation controllers to enable demand-side water management and reduce peak freshwater demand [27] • Used digital technologies (e.g. IoT, AI, digital twins) to improve water monitoring and management, reducing freshwater use in Spain [5] • Used digital twins and advanced metering infrastructure to optimise water distribution and control leakage, lowering water loss [28]
<i>Optimising value of water</i>	<i>Redistribute</i>	Optimising water use by allocating water resources based on the supply and demand across regions and time periods	<ul style="list-style-type: none"> • Assessed multi-regional benefits of a large-scale water diversion project using integrated modelling to balance supply and demand across regions [29] • Optimised national-scale water supply and transfer systems through cost-effective design, enabling water sharing to balance supply and demand [30] • Built a smart water grid with a digital twin for real-time monitoring and scenario analysis, reducing leakage and improving network efficiency [31]
	<i>Reuse</i>	Cascading applications of water with minimal or no additional treatment	<ul style="list-style-type: none"> • Used process simulation combined with machine learning to optimise industrial circulating cooling water systems, reducing total economic cost through better water reuse [32]
	<i>Recycle</i>	Turning the used water into its original or lower-quality standards through treatment, typically followed by Reuse	<ul style="list-style-type: none"> • Applied digital technologies (e.g. IoT, AI, digital twins) in wastewater treatment to recycle water, recover energy and nutrients and lower operational costs [9] • Used AI to match recycled water supply with demand, supporting circular water system • Developed a hybrid machine learning approach to assess treated wastewater quality for agricultural recycling, enabling safe irrigation [10]
	<i>Recover</i>	Extracting valuable resources, such as nutrients, energy and materials, from wastewater.	<ul style="list-style-type: none"> • Assessed metal recovery from wastewater and brine from techno-economic and supply-risk perspectives, identifying priority metals and guiding recovery processes [33] • Reviewed the shift from pollution control to resource recovery in sewage management, focusing on recovering organic carbon as bioenergy and nitrogen and phosphorus as nutrients, while summarising advances in high-value recovery technologies [34]
<i>Maximising water resource generation</i>	<i>Restore</i>	Replenishing water resources from rainwater, groundwater, river and wetland	<ul style="list-style-type: none"> • Used a circular economy model to implement rainwater harvesting systems, reducing suspended solids and turbidity while replenishing water resources [35]
	<i>Regenerate</i>	Upgrading of water quality to a higher standard than its previous use	<ul style="list-style-type: none"> • Evaluated decentralised wastewater treatment with reverse osmosis and pre-treatment, showing that digital monitoring and advanced treatment can upgrade wastewater to potable standards [36] • Using self-healing technologies to turn wastewater into a potable resource [3]

[43,44]. In this paper, *Reuse* refers to cascading applications of water with minimal or no additional treatment, whereas *Recycle* means turning the used water into its original or lower-quality standards through treatment, typically followed by *Reuse*. Digital technologies increasingly optimise these processes through real-time monitoring and control of treatment operations, automated adjustment of treatment parameters [34], early detection of anomalies or emerging contaminants [45] and reductions in chemical inputs [16]. Integrated digital systems combining IoT, AI

and blockchain have the potential to significantly improve reuse and recycling rates [17].

Digital platforms can also support cross-sectoral water *Reuse* by matching sources of treated wastewater with suitable downstream users. Recent studies show how digital tools identify symbiotic opportunities, enabling wastewater from one sector to be reused for another with minimal treatment [46], for instance, using AI to advance treated water reuse for agricultural irrigation [10]. Such

Figure 1



Digital technologies for 7Rs circular economy in the water sector.

coordination is critical for scaling reuse towards system-level circularity.

Recover strategy focuses on extracting valuable resources (e.g. nutrients, energy and materials) from wastewater [44,47]. Real-time sensing, AI and digital twins are increasingly used to optimise recovery, reducing chemical and energy use while maximising extraction of critical resources [33,48]. Digital tools also support distributed water treatment [1], creating economic value from recovered resources and transforming wastewater treatment plants from cost centres into multi-resource recovery hubs [6]. Recent work highlights that digital platforms support cross-sectoral integration by linking recovered resource supplies with industrial and agricultural demands [5], a prerequisite for scalable circular water-energy-nutrient systems [49].

Maximising water resource generation: restore, regeneration

Restore focuses on replenishing water resources from rainwater, groundwater, rivers and wetlands [20,23]. Recent studies demonstrate how digital solutions maximise rainwater harvesting [35], manage groundwater resources [50] and improve river restoration [51]. These

capabilities are essential for long-term water security and climate resilience [6].

Finally, this paper further proposes *Regeneration* as a new circular strategy, referring to the upgrading of water quality to a higher standard than its previous use. Although similar concepts exist in literature, they are often framed under *Reclaim* — typically defined as wastewater treatment and its subsequent use outside the original loop [20]. Such classifications, however, do not distinguish between water reused at the same or lower quality and water deliberately upgraded to a higher standard.

Introducing *Regeneration* explicitly differentiates *re-generated water* (with upgraded quality) from *recycled water* (with equivalent or lower water quality), thereby highlighting the principle of *using high-quality treated water for high-value applications*. This distinction is important as it aims to maximise the value of treated water based on its quality. Although the term *Regeneration* appears in literature (e.g. in [22]), it is not defined in a quality-centric manner and is conceptually closer to *restore*. Empirical research addressing digital technologies for regenerating water remains limited; however, emerging studies on advanced treatment highlight the importance of digitalisation in upgrading water quality [34,44,47,49,52].

Key digital functions that enable circular economy in water system

Our review shows that the 7Rs are rarely enabled by a specific digital technology; instead, they often depend on integrated digital systems that integrate data collection (e.g. through IoT), data processing and analytics (e.g. through AI, cloud computing) and automated control (e.g. through robotics). Fundamentally, circular strategies are realised through the functions that digital technologies perform, rather than the technologies themselves.

Building on [7], we identify ten key digital functions most relevant to circular water systems: *connect, monitor, optimise, forecast, assess, detect, track & trace, auto-plan, auto-control* and *visualise* (Figure 1). Current evidence shows that these functions are most extensively studied for Reduce, Recycle and Recover, indicating that they are relatively mature and most applicable in the water sector. In contrast, studies and applications in Reuse, Redistribute and Restore remain limited, while Regeneration is largely unexplored, revealing significant gaps and priority directions for future research.

Key factors for successful adoption of digital technologies in circular water systems

The successful adoption of digital technologies depends not only on technical capability but also on economic viability, institutional capacity and social acceptance.

A first critical factor is *data quality and technical architecture* [8,53]. Digital water systems rely on continuous, high-quality data streams for monitoring, prediction and automated control. In practice, data reliability is often affected by sensor malfunction, inadequate data collection frequency, missing values or poor interoperability between systems [16,48]. Addressing these challenges requires robust sensing infrastructure and standardised protocols for data collection, storage and sharing across organisations and sectors [54]. As water infrastructure is often classified as critical national infrastructure, data security and cybersecurity are essential to minimise societal risks [55]. Digitalisation also introduces trade-offs. For example, inefficient AI systems may increase the data centres' energy demand and associated water use for cooling. Ensuring safe and responsible deployment of digital technologies is therefore critical for achieving sustainable circular water systems [56].

Second, digital circular water solutions require sustainable business models [28,53]. Recent practices show that many publicly funded digital water projects have struggled to sustain once external support ends [46]. The upfront costs of digital systems outweigh short-term benefits, particularly in wastewater treatment, where services are rarely profitable without subsidies [25,53,57]. Successful cases increasingly point towards business models that either

create new revenue streams — such as through monetising recovered energy, nutrients or materials — or deliver substantial cost savings by improving efficiency, reducing water losses and optimising resource use [6,44,58]. Without viable business models, digital solutions risk remaining confined to pilot scale.

Finally, institutional and social factors are also essential for scaling. Many water authorities face shortages of skilled personnel, limited digital literacy and organisational capacity to adopt advanced digital tools [57,59]. Overcoming these barriers requires sustained investment in skills development [4,6], interdisciplinary collaboration between water engineers, data scientists and policymakers [9,16], and supportive policies and regulations that incentivise digital innovation [53,56]. Public acceptance, particularly for recycled and regenerated water, is equally critical and depends on transparency, risk management and effective communication to build trust among users [60].

Conclusion

Water is a special natural resource. Unlike many materials, water quality can return to its original or even higher standards, enabling repeated and high-value use across sectors. This unique property creates substantial yet still largely underexploited potential for a circular water system. Digital technologies play an essential role in unlocking this potential.

Over the past two years, digitalisation has evolved from a supporting role to a core enabler of circular water systems, shifting from reactive management to predictive, system-level optimisation. It not only improves efficiency but also increasingly supports demand reduction, water reallocation, reuse and recycling and resource recovery.

This paper proposes a consolidated 7Rs circular economy framework for the water sector and examines how digital technologies enhance circular strategies. In particular, it introduces *Regeneration* as an emerging but underexplored frontier, emphasising the upgrading of water quality for high-value applications. Our review shows that the 7R circular strategies are rarely enabled by single technologies, but by integrated digital systems and their underlying functions. We identify 10 key digital functions and find applications most advanced in *Reduce*, *Recycle* and *Recover*, with *Reduce* offering a particularly accessible, high-impact strategy for practitioners that can be implemented with relatively low investment while delivering long-term economic benefits. The paper also highlights that digitalisation requires robust technological capability, viable business models, institutional capacity and social acceptance.

Looking ahead, four priorities emerge. First, more research is needed on *Reuse*, *Redistribute* and *Restore*, which remain underexplored compared to the dominant focus on Reduce, Recycle and Recover. Second, the concept of *Regeneration*, introduced here as a separate R-strategy, represents a critical gap and requires further investigation, particularly regarding how digitalisation could support the upgrading of water quality for high-value applications beyond reuse and recycling. Third, future research should move beyond a technology-centric focus towards system-level design that links digital innovation to circularity across multiple R-strategies. Fourth, more work is required on business models, governance and policies that align digital innovation with long-term economic and societal value creation.

Data Availability

Data will be made available on request.

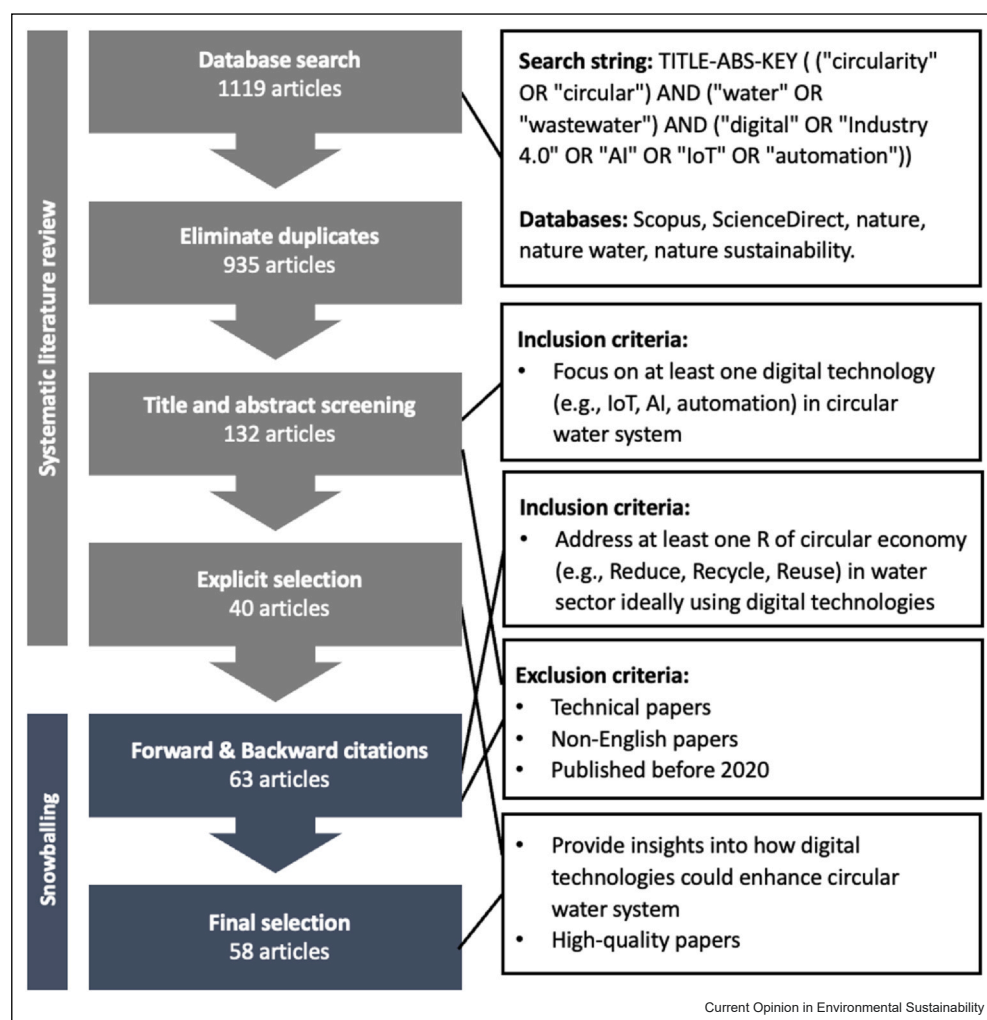
Declaration of Competing Interest

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



An overview of literature review process.

Table A1

An overview of the distribution of papers.								
R strategy	Year of publication							
	2020	2021	2022	2023	2024	2025	2026	Total
Reduce	1	-	-	2	6	10	8	27
Redistribute	1	-	-	2	8	3	2	16
Ruse	1	-	-	1	6	7	6	21
Recycle	2	1	1	1	9	13	16	40
Recover	1	-	-	-	10	9	11	31
Restore	1	-	-	1	3	3	2	10
Regenerate	-	-	-	-	-	3	2	5

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

1. Garrido-Baserba M, Sedlak DL, Molinos-Senante M, Barnosell I, Schraa O, Rosso D, *et al.*: **Using water and wastewater decentralization to enhance the resilience and sustainability of cities.** *Nat Water* 2024, **2**:953-974, <https://doi.org/10.1038/s44221-024-00303-9>.

This study evaluates decentralised water and wastewater systems using source separation technologies and shows that they can substantially enhance resource recovery efficiency. It highlights the role of digital tools in supporting the spread of distributed water treatment, and demonstrates on-site reuse of recovered resources — such as vertical farming, renewable energy generation and rainwater harvesting — illustrating a true circular urban economy.

2. European Environmental Agency: **Europe's State of Water 2024: The Need for Improved Water Resilience.** Publications Office of the European Union; 2024.
3. Narendra K, Manjushree M, Adur AJ, Raajasubramanian D, Srinivasan S, Murali R: **Self-healing water systems: the future of smart, adaptive, and regenerative water networks.** *Clean Water* 2025, **4**:100112, <https://doi.org/10.1016/j.clwat.2025.100112>.

This paper introduces the concept of self-healing water systems, presenting a transformative paradigm for future water infrastructure that integrates AI, smart sensing, nanotechnology, and microbial processes. It demonstrates how these systems can autonomously monitor, adapt, and repair, enhancing resilience, efficiency, and resource recovery. Importantly, the paper advances a regenerative vision for water management, while critically addressing challenges related to scalability, cost, governance, and technological integration in real-world deployment.

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This study explores how digital tools are reshaping water management and policy in Spain, analysing their key impacts in four aspects: monitoring and data collection, predictive analytics and decision support, efficiency and resource optimisation, and stakeholder engagement and governance. It demonstrates tangible operational benefits while revealing adoption challenges across managerial scales, and is important for showing how national funding and public-private partnerships can modernise institutions and strengthen climate-resilient water management

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This paper introduces the WICER Framework, clarifying how circular economy principles apply to the water sector and identifying nine key

actions for achieving circular and resilient outcomes. It is important for providing practical guidance to governments and practitioners on capturing water's full value, designing out waste and pollution, delivering inclusive, resilient services, and regenerating natural systems.

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- Multidisciplinary Digital Publishing Institutet (MDPI). This paper presents a review of smart water system developments, mapping technological maturity, geographic distribution, and implementation challenges. It traces the evolution from smart meters to digital twins and highlights how digital tools enhance monitoring, optimisation, and resilience. The study identifies cybersecurity and stakeholder engagement as key barriers and calling for standardised benchmarking to demonstrate benefits of digital infrastructure.
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