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Circular Economy in the Urban Water Cycle

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Abstract

The integration of circular economy principles into the urban water cycle aims to transition from the conventional linear management model toward a resource-efficient and regenerative framework. Traditionally, urban water systems are based on a sequence of water abstraction, drinking water treatment, distribution, consumption, wastewater collection, treatment, and discharge. Although this approach has ensured reliable water supply and sanitation services, it is associated with significant challenges, including high energy requirements, resource inefficiencies, and environmental pressures. Circular economy strategies seek to close material and energy loops by minimizing resource consumption, maximizing water reuse, recovering valuable by-products, and restoring natural ecosystem functions. Within this framework, advanced monitoring technologies, smart sensors, and leakage detection systems contribute to improving operational efficiency and reducing water losses. At the same time, treated wastewater can be reclaimed for agricultural, industrial, urban, and, under stringent regulatory conditions, potable applications. Wastewater treatment plants are progressively evolving into water resource recovery facilities (WRRFs), capable of producing renewable energy through biogas generation and recovering nutrients such as phosphorus and nitrogen for agricultural reuse. Furthermore, the integration of micro-hydropower technologies and pumped-storage systems strengthens the water–energy nexus by enhancing energy efficiency and facilitating renewable energy integration. Nature-based solutions, including Sustainable Urban Drainage Systems (SUDS), rainwater harvesting, and ecosystem restoration initiatives, further improve urban resilience to flooding and drought events. Although the adoption of circular water management practices offers substantial environmental, economic, and social benefits, their large-scale implementation requires technological innovation, significant investment, supportive regulatory frameworks, and broad stakeholder engagement.

Keywords: Urban water cycle; circular economy

Introduction

Water constitutes a strategic natural resource that underpins public health, economic development, and ecosystem sustainability. In urban environments, increasing population density, industrial activity, and socioeconomic development have led to a continuous rise in water demand, placing growing pressure on available water resources. Furthermore, climate change is altering hydrological

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regimes through changes in precipitation patterns, increasing the frequency and severity of droughts and floods, and exacerbating water scarcity in many regions worldwide. These challenges have exposed the limitations of conventional urban water management approaches and highlighted the need for more resilient and sustainable solutions. The urban water cycle comprises a series of interconnected processes, including water abstraction from natural sources, drinking water treatment, distribution through supply networks, consumption by domestic, industrial, and commercial users, wastewater collection, treatment, and final discharge into receiving water bodies. Traditionally, this system has been managed according to a linear paradigm in which water and associated resources are used once and subsequently disposed of after treatment [1]. Although this model has ensured reliable water supply and sanitation services, it is characterized by substantial energy consumption, significant water losses within distribution systems, and the underutilization of potentially valuable resources contained in wastewater, such as nutrients, organic matter, and recoverable energy.

In response to these challenges, the circular economy concept has emerged as a transformative framework for sustainable resource management [2]. Promoted by international organizations and policy initiatives, including those of the European Union [3], the circular economy seeks to decouple economic growth from resource consumption by maximizing resource efficiency, minimizing waste generation, and promoting the recovery and regeneration of materials and energy flows. When applied to urban water systems, this approach aims to close water, energy, and nutrient cycles through strategies such as water reuse, resource recovery, energy generation, and ecosystem restoration, thereby enhancing both environmental sustainability and system resilience [4]. The objective of this study is to evaluate the integration of circular economy principles within the urban water cycle, with particular emphasis on their technological applications, environmental and socioeconomic benefits, and the main technical, regulatory, and operational challenges associated with their implementation.

The Traditional Urban Water Cycle

The urban water cycle [5] comprises all the processes required to supply water to the population and manage the wastewater generated.

This cycle includes the following stages:

a. Water abstraction: extraction of water from rivers, reservoirs, or aquifers.

b. Drinking water treatment: treatment processes that make water suitable for human consumption.

c. Distribution: transport of water through urban supply networks.

d. Consumption: domestic, industrial, and commercial uses.

e. Sewerage collection: collection of wastewater.

f. Wastewater treatment: treatment of wastewater prior to discharge.

g. Discharge: return of treated water to the natural environment.

Although this system has ensured reliable water supply in urban areas, it presents significant limitations. These include water losses in distribution networks, high energy consumption associated with treatment and transport processes, and environmental pollution caused by wastewater discharges. Moreover, this model fails to exploit the resource potential of wastewater, which contains recoverable water, energy, and nutrients that could be reused within a circular framework.

Circular Economy Concept Applied to Water

The circular economy is a model that seeks to replace the traditional "take–use–dispose" approach with one in which resources remain in use for as long as possible [6]. This concept is closely linked to sustainable development, as it aims to minimize environmental impacts while optimizing resource utilization. Applied to water management, the circular economy implies transforming the way the urban water cycle is managed. Instead of considering wastewater as a waste product, it is viewed as a valuable source of resources that can be recovered and reused [7].

The fundamental principles of this approach, applied throughout the water cycle, are [8]:

a. Reducing water and energy consumption.

b. Reusing treated water for multiple purposes.

c. Recovering materials and energy from wastewater.

d. Regenerating natural systems associated with the water cycle.

This paradigm shift requires not only technological innovation but also changes in management practices, regulatory frameworks, and public perception of water resources. A schematic representation of the urban water cycle incorporating circular economy principles is shown in the following figure.

Applications in the Urban Water Cycle

Circular economy principles can be applied at multiple stages of the urban water cycle, following the concepts of reducing, reusing, recovering, and regenerating resources.

Reducing consumption and improving efficiency

The primary objective is to minimize water and energy use throughout the entire system. To achieve this, several measures can be implemented to improve the efficiency of water infrastructures:

a. Leak detection and repair in distribution networks.

b. Use of digital technologies and sensors to optimize system management.

c. Reduction of energy consumption in pumping and water transport.



Figure 1: Urban Water Cycle Incorporating Circular Economy Principles [9].

These actions reduce both resource demand and operational costs, thereby improving the sustainability of urban water systems. Several cities provide successful examples of the practical application of these principles. In Amsterdam, integrated strategies have been developed that combine energy recovery in wastewater treatment plants, nutrient recovery, and the use of green infrastructure for stormwater management [10]. Similarly, Singapore stands out for its advanced potable water reuse system, known as NEWater, which enables the city-state to nearly close its water cycle despite its limited natural water resources [11]. In Barcelona, reclaimed water is used for irrigating green spaces, urban cleaning, and industrial applications, significantly reducing the demand for potable water [12]. These examples demonstrate that the application of circular economy principles in the urban water cycle is not only feasible but also an effective solution for improving urban sustainability and resilience.

Water reuse

One of the most important strategies is the reuse of treated wastewater. After appropriate treatment, reclaimed water can be used for:

a. Agricultural irrigation and landscape irrigation.

b. Industrial applications.

c. Urban cleaning.

d. Aquifer recharge.

The following case studies illustrate the practical implementation of these circular economy strategies within urban water systems. In Los Angeles (USA), water reuse is a key strategy for addressing chronic water scarcity. Recycled water is used for irrigating golf courses, parks, and public spaces, as well as for industrial applications. In recent years, the city has promoted ambitious wastewater recycling projects aimed at reducing dependence on external water sources such as the Colorado River [13]. In Perth (Australia), water reuse focuses on aquifer recharge. Treated wastewater undergoes advanced purification processes before being injected into underground aquifers, helping to maintain groundwater levels and secure future water supplies. This system is particularly relevant in a region affected by declining rainfall [14]. Orange County (USA) operates one of the world's most advanced groundwater recharge systems. Through the Groundwater Replenishment System, wastewater is purified using microfiltration, reverse osmosis, and disinfection before being infiltrated into underground aquifers. This process provides a sustainable and reliable source of indirect potable water [15].

In Singapore, the NEWater program is recognized globally as a model for advanced water reuse. Wastewater is treated to an extremely high level of purity and is used both in industrial processes and for indirect potable reuse through blending with reservoir water. This strategy has enabled the country to reduce its dependence on imported water [16]. In Windhoek (Namibia), direct potable reuse has been implemented for several decades. Due to its arid climate, the city has developed systems capable of treating wastewater to drinking-water standards. This pioneering approach has demonstrated that direct potable reuse is a viable solution in areas facing severe water scarcity [17]. In San Diego (USA), the Pure Water Program aims to transform wastewater into drinking water through advanced technologies such as membrane filtration and ultraviolet disinfection. The goal is to provide a sustainable local water source, reducing dependence on imported water and increasing resilience to droughts [18]. In Madrid

(Spain), reclaimed water reuse is fully integrated into urban water management. Following tertiary treatment, reclaimed water is used for irrigating large parks and public gardens, as well as for street cleaning and urban washing operations. This system significantly reduces potable water consumption for non-potable applications and optimizes the city's water resources [19].

Resource and energy recovery

Wastewater contains organic matter and nutrients that can be recovered and utilized. Wastewater treatment plants are increasingly evolving into facilities capable of:

a. Producing biogas from sewage sludge.

b. Generating electricity.

c. Recovering phosphorus and nitrogen for fertilizer production.

In addition, energy can be recovered within urban water systems through micro-hydropower technologies, which utilize pressure and elevation differences in water supply and sewer networks to generate electricity. Furthermore, pumped-storage hydropower plants can store energy by moving water between reservoirs located at different elevations. Although these systems do not directly reduce water consumption, they optimize the use of renewable energy sources and strengthen the efficiency of the water-energy nexus. The following case studies illustrate the practical implementation of these circular economy strategies within urban water systems. In Copenhagen (Denmark), wastewater treatment plants have evolved toward energy self-sufficiency. At the Lynetten plant, sludge generated during wastewater treatment undergoes anaerobic digestion to produce biogas. This biogas is used to generate electricity and heat, covering most of the facility's energy needs and even supplying surplus energy to the grid [20].

In Madrid (Spain), several wastewater treatment plants, including those integrated into the Valdemingómez complex, use sewage sludge to generate biogas. This biogas is converted into electrical and thermal energy, which is reused within the treatment process, reducing costs and emissions. This approach transforms treatment plants into key infrastructures within the urban circular economy [21]. In Amsterdam (Netherlands), in addition to energy production from biogas, wastewater treatment facilities are notable for nutrient recovery. Through specific processes, phosphorus is extracted in the form of struvite, which is subsequently used as agricultural fertilizer. This closes the nutrient cycle and reduces dependence on mineral resources [21]. In Milwaukee (USA), the wastewater treatment system has pioneered the valorization of by-products. Through the Milorganite program, nutrients such as nitrogen and phosphorus are recovered and transformed into commercial fertilizers, as shown in Figure 2. Simultaneously, the biogas produced during treatment is used for energy generation, further enhancing system sustainability [22].

In Portland (USA), micro-hydropower technologies have been installed within the drinking water distribution network. Small turbines placed inside pipelines take advantage of water pressure and elevation differences to generate electricity without affecting water supply, transforming the network into an additional source of renewable energy [23]. In Lucerne (Switzerland), the Alpine topography is utilized to install microturbines within the urban water network. These systems generate electricity from water flow and elevation differences, integrating energy production directly into the city's hydraulic infrastructure [24]. The Dinorwig Hydroelectric Power Station (Wales) illustrates the role of water in energy storage. The facility uses surplus electricity to pump water to an upper reservoir and releases it when demand increases, generating electricity rapidly. This system plays a key role in balancing electrical grids with a high penetration of renewable energy sources [25]. In Spain, several pumped-storage facilities, such as the La Muela Hydroelectric Power Plant in Valencia, perform a similar function. These facilities store energy generated from renewable sources by pumping water between reservoirs located at different elevations, contributing to grid stability and strengthening the integration between water management and energy systems [26].



Figure 2: Fertilizer Produced from the Recovery of Nutrients such as Nitrogen and Phosphorus [22].

Regeneration and Nature-Based Solutions

Finally, the circular economy promotes the regeneration of natural systems associated with the water cycle through:

a. Sustainable Urban Drainage Systems (SUDS).

b. Rainwater harvesting and utilization.

c. Restoration of urban ecosystems.

These solutions improve infiltration, reduce surface runoff, and increase resilience to floods and droughts by integrating the urban water cycle with the natural environment. The following case studies illustrate the practical implementation of these circular economy strategies within urban water systems. In Copenhagen (Denmark), Sustainable Urban Drainage Systems (SUDS) have become a key element of urban planning following severe flooding events. The city has transformed streets, parks, and public spaces into infrastructures capable of absorbing and retaining stormwater through permeable pavements, floodable green areas, and temporary storage basins. These solutions reduce runoff, prevent sewer overloading, and increase resilience to extreme weather events [27]. In Rotterdam (Netherlands), urban design integrates water as a central element through innovations such as water squares. These spaces function as recreational areas under normal conditions but are transformed into temporary storage basins during heavy rainfall events. This approach combines hydraulic functionality with social use, contributing to sustainable urban drainage management [28]. In Berlin (Germany), rainwater harvesting and utilization are promoted through urban policies encouraging green roofs, building-scale collection systems, and water reuse for irrigation and other non-potable purposes. These measures reduce pressure on wastewater infrastructure and decrease potable water consumption by integrating water management directly into urban architecture [29].

In Tokyo (Japan), rainwater harvesting is widely implemented in public buildings and major urban infrastructures. Collected water is stored and reused for applications such as cleaning and irrigation, contributing to more efficient water resource management in one of the world's most densely populated metropolitan areas [30]. In Seoul (South Korea), the restoration of the Cheonggyecheon Stream represents an emblematic example of urban ecosystem recovery. The removal of an elevated highway allowed a natural watercourse to be reintroduced into the city center, improving biodiversity, reducing the urban heat island effect, and increasing natural drainage capacity during intense rainfall events [31]. In Vitoria-Gasteiz (Spain), the development of the Green Belt has enabled the restoration of wetlands and natural areas surrounding the city. These spaces act as infiltration and water regulation zones, helping to manage stormwater naturally, reduce flood risks, and improve urban resilience to drought conditions [32].

Benefits and Challenges

The implementation of circular economy principles in the urban water cycle offers numerous advantages:

a. Reduction in potable water consumption.

b. Decrease in environmental pollution.

c. Recovery and valorization of resources.

d. Increased resilience to droughts.

However, significant challenges also remain:

a. High initial investment costs.

b. Need for regulatory and legislative changes.

c. Technical complexity.

d. Social acceptance issues, particularly regarding potable water reuse.

Overcoming these barriers requires public-private cooperation among governments, water utilities, industries, and citizens. In the coming years, collaborative efforts among all stakeholders will be essential to achieving meaningful and effective improvements in urban water management.

Conclusions

The adoption of circular economy principles within urban water systems offers a strategic pathway toward enhancing sustainability, resource efficiency, and resilience in water management. By promoting the closure of water, energy, and nutrient loops, circular approaches enable the recovery and valorization of resources embedded in wastewater streams while reducing environmental pressures associated with water abstraction, treatment, and discharge. Such strategies contribute to improving water security, particularly in regions facing increasing water stress driven by climate change, population growth, and urbanization.

However, the transition from conventional linear water management models to circular systems requires overcoming significant technical, economic, regulatory, and societal barriers. Successful implementation depends on the development of innovative technologies, adequate investment frameworks, supportive policies, and effective governance mechanisms. Furthermore, stakeholder engagement and public acceptance are essential, particularly for applications involving water reuse and resource recovery. In this context, the future of urban water management will increasingly rely on integrated and circular solutions capable of optimizing resource utilization, minimizing waste generation, and strengthening the interconnections between water, energy, and environmental systems. Such an approach is fundamental to achieving long-term urban sustainability while ensuring the preservation and responsible use of natural resources.

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Conflict of interest

No Conflict of Interest.

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