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Editorial

Circular Water Resources Integrating Sustainability and Innovation in Wastewater and Water Management

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Accessible freshwater, which is already limited, is threatened by overdemand and mismanagement, and the triple planetary crisis of climate change, biodiversity loss, and pollution is pushing the hydrological cycle out of balance [1–6]. Addressing this looming crisis requires a shift from a linear use-and-dispose model towards a circular one, where water and resources within wastewater are kept in use at their highest possible value [7–9].

The Special Issue “Editorial Board Members’ Collection Series: Water Resources” contributes to this discussion with a collection of eight studies that explore strategies for conserving water, recovering resources, and reducing environmental footprints across diverse contexts. The articles span topics from post-fire erosion control to advanced wastewater treatment plant upgrades, unified by a focus on sustainability and innovation. This editorial summarizes their findings, highlighting the ways in which they collectively advance circular water management.

One important dimension of circular water management is the protection of catchments and soils that mediate runoff and infiltration [10–15]. Navidi et al. [16] examined whether applying biodegradable mulch made from yellow mistletoe fruits (*Loranthus europaeus* Jacq.) mixed with straw could help mitigate post-fire hydrological hazards in semi-arid pine forests. Wildfires remove vegetation and litter, expose soil to rainfall, and generate hydrophobic layers that reduce infiltration, amplifying runoff and erosion risks. In rainfall simulations, mulching increased total runoff compared with untreated burned soil but significantly delayed peak flow and reduced its intensity. Most strikingly, rain-splash erosion was reduced by up to 97%. The results suggest that biodegradable mulches from invasive mistletoe species, which are often considered to be a waste product, can be repurposed to protect burned landscapes and help maintain soil functions after fires. Such nature-based solutions reflect a circular perspective by turning biomass residues into valuable tools for ecosystem recovery.

Wastewater treatment itself is a cornerstone of circular water management [17–20]. Mascoli Junior et al. [21] evaluated a multistage constructed wetland (the EvaTAC system) treating greywater from household activities. Greywater contains surfactants such as linear alkyl benzene sulfonate (LAS) that are widespread in detergents and can harm aquatic life. A test lasting approx. 500 days demonstrated that the wetland achieved removal efficiencies of 66% for chemical oxygen demand (COD) and 43% for LAS. DNA sequencing revealed diverse microbial communities performing hydrolysis, fermentation, syntrophy, methanogenesis, and surfactant degradation, with Pseudomonas species dominating among LAS degraders. The study also noted a positive correlation between COD and LAS removal, indicating that COD could serve as a surrogate design parameter for surfactant removal.

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These findings illustrate how nature-based treatment systems harness microbial diversity to improve effluent quality, enabling safe greywater reuse in households or irrigation while recovering water for additional cycles.

Beyond greywater, municipal wastewater offers nutrient-rich media for cultivating microalgae. Dammak et al. [22] reviewed the state of microalgae-based municipal wastewater treatment and biomass production. Microalgae remove nutrients and contaminants while producing valuable biomass for biofuels, animal feed or nutraceuticals. The authors emphasized that integrating microalgal cultivation with municipal wastewater treatment aligns with the circular economy concept because it simultaneously treats effluent and generates biomass without producing secondary pollution. However, challenges remain with regard to scaling up, maintaining stable microalgae–bacteria consortia, controlling environmental conditions, and balancing nutrient ratios. The review highlighted the need to explore native microalgal consortia adapted to effluent conditions and to develop cost-effective harvesting methods. Progress in this area could transform wastewater treatment plants from energy-intensive units into biorefineries that recover water, nutrients, and renewable biomass.

While nature-based and biological systems offer important sustainability gains, computational tools are also crucial for strategic planning of interventions at watershed scales [23–26]. Miele et al. [27] used the Soil and Water Assessment Tool (SWAT) to assess the effectiveness of various best management practices (BMPs) for reducing phosphorus loads from the flat Wigle Creek watershed in southern Ontario, Canada. They developed a high-resolution digital elevation model (DEM) to represent flow pathways and calibrated the model for flow, sediment, and phosphorus transport. Modelling results showed that converting croplands to pasture or forest substantially reduced the phosphorus loads that reached Lake Erie, whereas winter wheat cover crops had little effect. The study underscores how hydrological modelling can guide resource-efficient BMP implementation when field monitoring is costly and logistically challenging. Such computational approaches allow stakeholders to test land-use scenarios and tailor interventions to achieve water quality targets, reinforcing the nexus between land management, agricultural sustainability and water resources.

Infrastructure renewal is another domain where circular strategies can yield environmental benefits [28–30]. Chorazy et al. [31] compared the carbon footprints of trenchless and traditional excavation technologies used to restore ageing sewer networks in Brno, Czech Republic. Restoring sewer systems is essential for preventing leaks that contaminate groundwater and surface water, but conventional excavation is energy-intensive and disruptive. The authors calculated carbon emissions based on energy demand and found that the trenchless variant (cured-in-place pipe) emitted only 9.91 t CO_2 eq., whereas the traditional excavation method emitted 24.29 t CO_2 eq., a 59.2% reduction. The trenchless method also reduced fuel costs, waste disposal, and traffic disturbances. These findings demonstrate that adopting modern, low-impact technologies for sewer rehabilitation can decrease greenhouse gas emissions and support urban sustainability without compromising service quality.

The concept of ecosystem services provides a holistic framework for valuing water resources beyond their direct extractive use [32,33]. Iliopoulos and Damigos [34] observed that existing ecosystem service classifications often double-count benefits, fail to distinguish final and intermediate services, and overlook groundwater's unique attributes. Following a literature analysis and expert consultation, they proposed GROUNDWES, a unified classification system for groundwater ecosystem services. GROUNDWES aims to clarify definitions, avoid double counting, and categorize services as final or intermediate, thereby improving economic assessment and management policy research for aquifers. This work emphasizes that groundwater not only provides drinking water but also supports baseflow in rivers, nutrient cycling, and climate regulation. Recognizing these services can help integrate groundwater into environmental accounts and inform more balanced resource management strategies.

The oil and gas industry's "produced water" (PW), a by-product of hydrocarbon extraction, is often disposed of as a waste, despite its potential as a resource [35,36]. Alsalem and Thiemann [37] analyzed PW from South Kuwait and evaluated scenarios for using it as a water for enhanced oil recovery, as a source of industrial salts, or both. Kuwait produces roughly two million barrels of PW daily, yet it relies heavily on desalination for freshwater and imports minerals. The authors found that reusing PW in enhanced oil recovery could reduce freshwater consumption for extraction by up to 4.8% for the South Kuwait fields and by 42% if this practice is applied across the country. Treating PW for salt recovery could also supply local industries and generate new revenue streams. By valorizing a waste stream, these strategies embody circular economy principles, turning an environmental liability into a resource that supports water security and economic diversification.

Finally, Al-Khatib and AlHanaktah [38] documented the comprehensive upgrade of the Aqaba Conventional Activated Sludge Wastewater Treatment Plant (CAS-AWWTP) in Jordan and evaluated its linkage to multiple Sustainable Development Goals (SDGs). The upgraded WWTP increased its treatment capacity to 40,000 m^3/day by integrating renewable energy and repurposing natural treatment ponds as artificial wetlands. It achieved average removal efficiencies of 99.1% for BOD_5, 96.6% for COD, 98.7% for total suspended solids and 95.1% for total nitrogen, supplying about 30% of the Aqaba governorate's annual water budget. The facility achieved 44% electrical self-sufficiency and provided habitat for more than 270 bird species, attracting eco-tourism. By reducing its carbon footprint, supporting water reuse in agriculture and industry, promoting renewable energy and biodiversity conservation, and fostering partnerships, the project contributes to SDGs 6, 7, 8, 11, 12, 14/15 and 17. This case study illustrates how modern WWTPs can integrate technological efficiency with ecological restoration and socio-economic benefits.

Taken together, the studies in this Special Issue demonstrate how circular economy thinking can be applied across scales, from microbial processes in wetlands and biorefineries to watershed management, infrastructure renewal, and national water strategies. They all emphasize transforming waste streams into resources, reducing environmental footprints, harnessing biodiversity, and preserving the integrity of water ecosystems. The adoption of biodegradable mulching materials, nature-based greywater treatment, and microalgal systems highlights opportunities to integrate ecological processes into engineered systems. Both hydrological modelling of BMPs and carbon-footprint analysis of sewer restoration technologies provide tools for strategic planning and policy. The classification of groundwater ecosystem services underscores the need for coherent valuation frameworks, while the valorization of produced water and the holistic upgrade of the Aqaba CAS-AWWTP exemplify how integrated approaches can deliver multiple benefits.

Conventional linear approaches to water and wastewater management will be insufficient to cope with the threat of water scarcity [39–46]. The research curated in this Special Issue offers glimpses of a more resilient future in which water circulates through natural and engineered loops, resources are recovered rather than discarded, and infrastructure supports both human and ecological well-being [47–50]. Accelerating the adoption of circular water strategies will require cross-disciplinary collaboration, supportive policy frameworks, stakeholder engagement, and investment in research and development [51–55]. The experiences documented here, ranging from local case studies to conceptual frameworks, provide valuable lessons and inspiration for decision-makers, practitioners, and scientists committed to safeguarding water resources for present and future generations.

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