A Novel Integrated Circular Economy Framework for Public Water Infrastructure Systems: Integrating Global Strategies with National Policy Insights

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Abstract
Public water infrastructure systems are critical components of urban sustainability yet continue to operate under linear paradigms that contribute to resource depletion, environmental degradation, and escalating operational costs. This research proposes a novel integrated circular economy (CE) framework for public water infrastructure systems that combines global best practices with insights drawn from China's pioneering national circular economy indicator system. By synthesizing key concepts from studies on CE in water and wastewater management, digital innovations, and policy-driven governance models (e.g., Bleischwitz, Geng, & Sarkis, 2019; Ghisellini, Cialani, &Ulgiati, 2015; Joensuu et al., 2020; Potting et al., 2017; Preston, 2012; Smol, Adam, & Preisner, 2020; Velasco-Muñoz et al., 2021), and incorporating findings from national indicator research in China (Geng et al., 2012), the framework advocates for a system that emphasizes reduction, reclamation, reuse, recycling, recovery, and – critically – rethinking of water value chains. Digital technologies such as IoT sensors, digital twins, and big data analytics are integrated to facilitate real-time monitoring and adaptive management. Furthermore, the paper discusses how comprehensive policy instruments and measurable performance indicators can drive the transition from linear to circular water management. The proposed framework offers a pathway for decoupling economic growth from resource use, enhancing resilience, and improving the overall sustainability of public water infrastructure.

Keywords: Circular Economy, Public Water Infrastructure, Digital Integration, Policy Indicators, Sustainable Water Management

1. INTRODUCTION

Water infrastructure systems underpin public service delivery and urban resilience. Traditional water management operates on a linear "take–make–dispose" model, which exacerbates resource scarcity and environmental degradation. With increasing pressures from urbanization, climate change, and industrial growth, there is an urgent need for a paradigm shift toward circular economy (CE) principles that promote resource recovery and sustainable operation. This paper proposes an integrated CE framework for public water infrastructure systems that incorporates global best practices as well as insights from national policy initiatives—in particular, China's nationally developed circular economy indicator system (Geng et al., 2012). By reimagining water infrastructure as both a supply network and a resource recovery hub, the framework aims to achieve significant reductions in water and energy use, lower pollutant emissions, and enhance the longevity and resilience of infrastructure assets.

The paper is organized as follows. Section 2 reviews the literature on CE applications in water management and introduces the concept of national CE indicators as a policy tool. Section 3 describes the methodology for developing the integrated framework. Section 4 presents the proposed framework and its six core pillars. Section 5 discusses the implications of integrating digital innovations and policy indicators for decision-making, while Section 6 concludes with recommendations for research and practice.

2. LITERATURE REVIEW

The circular economy concept emerged as a counterpoint to linear production models, with early work by Pearce and Turner (1989) laying the theoretical groundwork. Since then, CE has evolved to encompass applications in industrial manufacturing (Ghisellini et al., 2015), agriculture (Velasco-Muñoz et al., 2021), the built environment (Joensuu et al., 2020), and water management (Smol et al., 2020). A recurring theme across these studies is the need to close resource loops and transform waste streams into valuable inputs.

2.1 Circular Economy in Water and Wastewater Management

Smol et al. (2020) propose a CE model framework for the water and wastewater sector that includes six actions: reduction, reclamation (removal), reuse, recycling, recovery, and rethinking. Their work demonstrates that effective water management can be achieved through technological innovation and improved operational practices, such as advanced pollutant removal and nutrient recovery. Complementarily, Potting et al. (2017) emphasize the role of innovation along product chains, with principles that are readily transferable to the water sector by designing assets for longevity and circularity.

2.2 Digital Innovations in Infrastructure Management

Recent literature has highlighted the transformative potential of digital technologies. Joensuu et al. (2020) illustrate how digital twins, IoT networks, and big data analytics can facilitate real-time monitoring and predictive maintenance in urban environments. In water infrastructure systems, such digital integration is essential for tracking resource flows, optimizing system performance, and enabling adaptive management. Bleischwitz et al. (2019) further argue that international data platforms are necessary to harmonize practices and accelerate the transition to circular models globally.

2.3 Policy Frameworks and Measurable Indicators

Effective policy is critical to driving CE transitions. Preston (2012) advocates for a global redesign of industrial systems to decouple economic growth from resource consumption. However, a significant gap in current research is the lack of comprehensive performance indicators that capture not only environmental and economic dimensions but also social and institutional factors. In this context, the work by Geng et al. (2012) on China's national circular economy indicator system offers valuable insights. China's pioneering efforts—through legislation such as the Circular Economy Promotion Law (China, 2009) and the development of quantitative indicators—demonstrate how policy can leverage measurable metrics to benchmark progress and drive improvements across multiple levels (macro, meso, and micro).

2.4 Integrating Global and National Perspectives

While many studies focus on sector-specific applications, integrating global CE strategies with national policy frameworks enhances the potential for widespread systemic change. The Chinese model provides an example of how CE indicators can inform policy, guide local implementation, and ultimately support national sustainability goals (Geng et al., 2012). This integration of measurable performance indicators with digital and operational innovations forms the basis of the updated framework presented in this paper.

3. METHODOLOGY

The revised research follows an integrative review and conceptual design methodology with three major phases:

3.1 Systematic Literature Synthesis

An exhaustive review of eight key research papers—including studies by Bleischwitz et al. (2019), Ghisellini et al. (2015), Joensuu et al. (2020), Potting et al. (2017), Preston (2012), Smol et al. (2020), and Velasco-Muñoz et al. (2021)—was undertaken to extract common CE principles and technological approaches relevant to water management. In addition, the national circular economy indicator system developed by Geng et al. (2012) was critically analyzed to understand how measurable performance metrics can guide policy implementation and operational improvements.

3.2 Conceptual Framework Development

Based on the synthesized literature, a conceptual framework was constructed. This framework integrates six core actions (reduction, reclamation, reuse, recycling, recovery, and rethink) with cross-cutting elements of digital integration and policy-based performance measurement. The inclusion of national CE indicators provides an evaluative mechanism to track progress and identify bottlenecks.

3.3 Integration of Digital and Policy Dimensions

Digital technologies (e.g., IoT, digital twins) and policy instruments (e.g., environmental taxes, extended producer responsibility) are mapped to each pillar of the framework. This dual focus ensures that technical innovations are supported by robust governance structures and measurable performance criteria derived from both international and Chinese national experiences.

4. PROPOSED INTEGRATED CIRCULAR ECONOMY FRAMEWORK

The updated framework for public water infrastructure systems is structured around six core pillars (Figure 1). It explicitly integrates digital innovations and policy indicators as enablers for operational transformation and sustainable management.

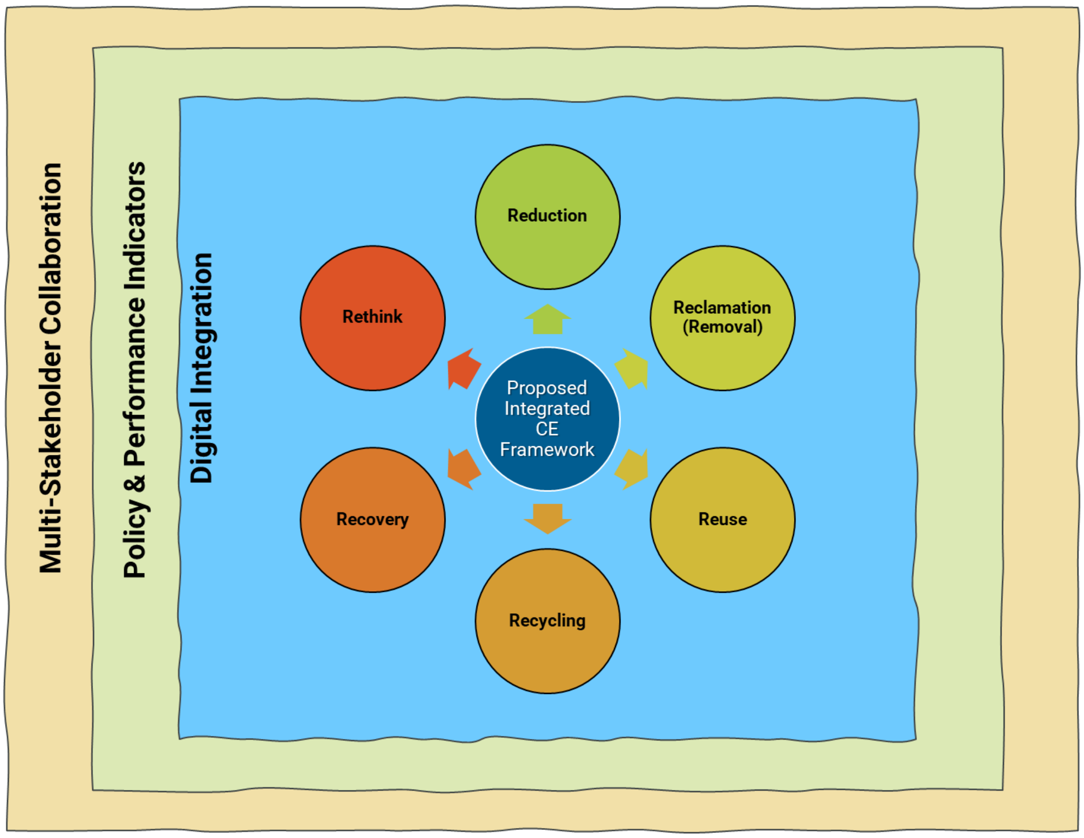
4.1 Reduction

Reduction targets both water loss and energy inefficiencies.

• Smart Monitoring and Leak Detection: IoT sensors and digital twins enable real-time identification of inefficiencies and leaks (Joensuu et al., 2020).

• Demand Management: Implementing water conservation programs and pricing strategies reduces overall consumption—a goal aligned with the "prevention" aspect highlighted in China's indicator systems (Geng et al., 2012).

Figure 1: Proposed Integrated Circular Economy Framework



4.2 Reclamation (Removal)

Reclamation involves the effective removal of pollutants from wastewater.

• Advanced Treatment Technologies: Adoption of membrane bioreactors, advanced oxidation processes, and nanofiltration (Smol et al., 2020) ensure contaminant removal to high standards, facilitating subsequent reuse or recycling.

• Modular Treatment Systems: Scalable, modular water treatment units allow for flexible responses to varying demands.

4.3 Reuse

Reuse strategies reintegrate treated water into the supply chain for non-potable applications.
• Non-Potable Applications: Treated wastewater can serve for agricultural, industrial, or urban landscaping purposes, reducing the pressure on freshwater sources (Smol et al., 2020).

• Decentralized Reuse Networks: Localized reuse systems foster regional self-sufficiency and reduce transportation-related energy losses.

4.4 Recycling

Recycling focuses on recovering water for potable uses and reclaiming valuable by-products.
• Nutrient and Energy Recovery: Technologies to recover phosphorus, nitrogen, and biogas from wastewater contribute to resource circularity (Potting et al., 2017).

• Membrane Technologies: Applications of nanofiltration and reverse osmosis are deployed for high-quality water recycling, offering alternatives to conventional water sources.

4.5 Recovery

Recovery extracts embedded value from water-based waste streams.

• Asset Optimization: Digital tools support the retrofitting and repurposing of aging infrastructure, thereby extending asset life and reducing capital expenditures (Joensuu et al., 2020).

• By-Product Valorization: Recovering resources—such as recycled nutrients from sewage sludge—creates additional revenue streams and reduces import dependency, a key policy goal identified in China's national framework (Geng et al., 2012).

4.6 Rethink

The "rethink" pillar calls for a holistic reassessment of water management practices and the underlying economic model.

• Integrated Governance and Participatory Planning: Establish multi-stakeholder platforms for co-creation of sustainable water strategies, informed by both international best practices and national indicator systems (Bleischwitz et al., 2019; Geng et al., 2012).

• Policy Innovation: Transition from command-and-control approaches to incentive-based policies that reward efficiency, eco-design, and resource recovery. This shift is supported by measurable indicators that benchmark performance across regions.

4.7 Cross-Cutting Digital and Policy Integration

Digital technologies and policy indicators intersect all pillars.

• Digital Twins and Big Data Analytics: These tools provide the real-time data required for predictive maintenance, operational optimization, and continuous improvement in water systems (Joensuu et al., 2020).
• National and International CE Indicators: Drawing on both the European monitoring frameworks (Smol et al., 2020) and China's national CE indicators (Geng et al., 2012), a comprehensive set of performance metrics is used to track progress, identify gaps, and guide policy adjustments.

• Open Data Platforms: Collaborative data-sharing platforms support multi-level benchmarking and facilitate adaptive governance, ensuring that improvements are evidence-based and transparent.

5. DISCUSSION

The integrated framework presented here advances the state of water infrastructure management by combining technological innovations, adaptive governance, and measurable performance indicators.

5.1 Decoupling Growth from Resource Use

One of the framework's primary goals is to decouple economic growth from resource consumption. By emphasizing reduction, reuse, and recovery, the model reduces reliance on virgin water sources and decreases energy consumption. The incorporation of policy indicators, as developed in China's national system (Geng et al., 2012), enables governments to monitor progress quantitatively and incentivize improvements.

5.2 Enhancing Operational Resilience through Digital Technologies

Digital integration—through IoT networks, digital twins, and big data analytics—allows water utilities to shift from reactive to proactive management. Predictive maintenance and real-time performance monitoring not only reduce operational costs but also extend the lifespan of infrastructure assets. This resilience is critical for cities facing climate variability and rapid urban growth.

5.3 Policy Implications and Governance

The transition toward a circular water economy requires robust policy frameworks that reward sustainable practices. As Preston (2012) and Bleischwitz et al. (2019) have argued, aligning economic incentives with environmental objectives is crucial. By integrating national indicators (Geng et al., 2012) with international best practices, policymakers can establish clear benchmarks and enforce accountability. In this context, the "rethink" pillar encourages a participatory approach that engages stakeholders at all levels—from municipal utilities to national regulators.

5.4 Challenges and Opportunities

While the framework offers a comprehensive pathway toward circular water management, several challenges remain. Institutional inertia, high capital costs for digital upgrades, and data interoperability issues may impede rapid implementation. Moreover, the integration of relative performance indicators with absolute resource use measures requires further refinement to capture the full scope of environmental impacts. Future research should focus on pilot implementations that test these integrated approaches, refine performance metrics, and develop standardized protocols for data collection and reporting.

5.5 Future Research Directions

Empirical case studies of water utilities implementing this integrated framework will be essential to validate and refine the proposed model. Further work is needed to develop standardized performance indicators that combine digital data analytics with policy benchmarks. Comparative studies between regions using European frameworks and those applying China's national indicators could yield insights into best practices for global CE transitions in the water sector.

6. CONCLUSION

This paper has presented an integrated circular economy framework for public water infrastructure systems that marries global best practices with national policy insights. By organizing the transition around six key pillars—reduction, reclamation, reuse, recycling, recovery, and rethink—and underpinning them with advanced digital technologies and robust policy indicators, the framework provides a comprehensive roadmap for transforming water infrastructure from a linear to a circular model.

The integration of China's national circular economy indicator system (Geng et al., 2012) into this framework offers policymakers and water utilities measurable tools to track progress, benchmark performance, and drive continuous improvement. This dual approach of technology and policy creates a resilient, adaptable system capable of decoupling economic growth from resource consumption and environmental impact.

Ultimately, the transition to a circular water infrastructure is not only technologically feasible but also economically and socially advantageous. By fostering collaboration among stakeholders, incentivizing sustainable practices, and leveraging digital innovations, cities can achieve more efficient resource use, reduce environmental burdens, and ensure a more sustainable future for urban water management.

References

1. Andersen, M. S. (2006). An introductory note on the environmental economics of the circular economy. *Integrated Research System for Sustainability Science*, 2(1), 133–140.

2. Bleischwitz, R., Geng, Y., & Sarkis, J. (2019). How to globalize the circular economy. *Nature Comment*, *565*, 153–155.
3. Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: An evaluation and critical analysis. *Journal of Cleaner Production*, *23*, 216–224.
4. Ghisellini, P., Cialani, C., &Ulgiati, S. (2015). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*.
5. Joensuu, T., Edelmana, H., & Saar, A. (2020). Circular economy practices in the built environment. *Tampere University, Faculty of Built Environment, Construction Management and Economics Research Group*.
6. Potting, J., Hekkert, M., Worrell, E., &Hanemaaijer, A. (2017). Circular economy: Measuring innovation in the product chain. *PBL Netherlands Environmental Assessment Agency*.
7. Preston, F. (2012). A global redesign? Shaping the circular economy. *Chatham House Briefing Paper*.
8. Smol, M., Adam, C., & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. *Journal of Material Cycles and Waste Management*, *22*, 682–697.
9. Velasco-Muñoz, J. F., Mendoza, J. M. F., Aznar-Sánchez, J. A., & Gallego-Schmid, A. (2021). Circular economy implementation in the agricultural sector: Definition, strategies, and indicators. *Resources, Conservation and Recycling*, *170*, 105618.