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An integrated multi-criteria framework for sustainability and circular economy assessment in public water utilities: Evidence from two anonymized Mediterranean case studies

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Abstract

Urban water utilities face increasing pressure to ensure sustainable, resilient, and efficient service provision under conditions of water scarcity, climate change, and growing regulatory demands. In Mediterranean regions, these challenges are further exacerbated by structural water stress, ageing infrastructure, and the need to transition towards circular water management models aligned with Sustainable Development Goal 6 (SDG 6).

This study proposes an integrated multi-criteria framework for sustainability and circular economy assessment in public water utilities, linking circular water economy strategies with water resilience objectives. The framework combines SDG 6–oriented indicators, environmental footprint analysis, ecosystem services assessment, social responsibility metrics, infrastructure performance indicators, and backcasting analysis within a Multi-Criteria Decision Analysis (MCDA) approach. Heatmap-based visualization is employed to support comparative assessment and enhance the interpretability of results.

The methodology is applied to two real public water utilities in Mediterranean urban contexts. Due to confidentiality constraints, the case studies are anonymized and referred to as Utility 1 and Utility 2. Results reveal distinct sustainability and circularity profiles, highlighting trade-offs and synergies between environmental performance, circular resource use, infrastructure robustness, and governance-related dimensions. The comparative analysis illustrates how different configurations of circular water management strategies contribute to enhanced water resilience, while also revealing context-specific limitations and strategic priorities.

The framework offers a replicable and adaptable decision-support tool for public water utilities seeking to operationalize sustainability, circularity, and resilience objectives. By integrating diverse indicator domains within an MCDA-based assessment, the approach supports evidence-based planning and strategic decision-making in water-scarce regions and comparable urban contexts.

1. Introduction

Urban water services are increasingly challenged by the combined effects of climate change, demographic pressure, ageing infrastructure, and rising expectations regarding environmental performance and social responsibility.

In Mediterranean regions, these pressures are amplified by structural water scarcity, high interannual variability of precipitation, and recurrent drought episodes, which expose vulnerabilities in conventional water supply and management models (Mekonnen and Hoekstra 2016; Albrecht et al. 2018). As a result, public water utilities operating in these contexts are required not only to ensure service reliability, but also to contribute actively to broader sustainability and resilience objectives, making sure that water use is done within limits and conservation practices are enhanced (Bach et al. 2014).

Moreover, utility companies have the important role to act as a pivotal sector to strengthen and guide the path towards sustainability in the applied policy domain. The main reasons are that their practices have a big impact (positive or negative) to the urban resources flow, manage critical resources such as water and energy, they are impacted by political, social and environmental factors and usually are the first subjects of new public policy frameworks, especially in regards to sustainability and circularity (D'Amato et al. 2019). This is even more marked in the public sector due to the tight link it has with governance and social legitimacy, making it even more mandatory for public utilities to incorporate transparent performance assessments regarding their social and environmental practices (Caputo and Fasiello 2024).

In response to these challenges, the concept of the circular economy has gained increasing attention in the water sector as a pathway to decouple service provision from resource depletion and environmental degradation (Geissdoerfer et al. 2018; Korhonen et al. 2018). Circular water economy strategies encompass a wide range of practices, including water reuse, energy recovery, resource valorization, demand management, and nature-based solutions, all of which aim to enhance system efficiency while reducing environmental impacts (van der Hoek 2012; Van Der Hoek et al. 2016). However, the implementation of circular approaches in water utilities remains uneven, often constrained by institutional fragmentation, regulatory barriers, and the lack of integrated assessment tools capable of capturing system-wide effects (Makropoulos and Butler 2010; Nika et al. 2020).

Beyond efficiency gains, recent literature highlights the importance of linking circular water management strategies with water resilience objectives, particularly in water-scarce regions (Rodina 2019; Butler et al. 2017). Water resilience refers to the capacity of water systems to anticipate, absorb, adapt to, and recover from disturbances while maintaining essential functions.

In this context, circularity and resilience should be understood as complementary rather than independent goals, requiring integrated analytical frameworks capable of assessing trade-offs, synergies, and long-term system robustness (Joss et al. 2017; Kallis 2010).

Sustainable development goal 6 as an integrated framework for water utilities assessment

The United Nations Sustainable Development Goal 6 (SDG 6) provides a comprehensive global framework for addressing water-related challenges, encompassing access to water and sanitation, water quality, efficiency, ecosystem protection, governance, and international cooperation (Programme 2018). For public water utilities, SDG 6 offers a valuable reference structure to align operational performance with sustainability objectives at multiple scales (Gain et al. 2016; Allen et al. 2016).

Despite its relevance, the operationalization of SDG 6 at the utility level remains challenging. Existing monitoring approaches often rely on fragmented indicator sets that fail to capture interdependencies between technical, environmental, social and governance dimensions (Nilsson et al. 2016k et al. 2016). Moreover, SDG indicators are typically designed for national-level reporting, requiring adaptation and

contextualization to support decision-making at the scale of urban water and sanitation services (Mannina et al. 2022).

Recent studies advocate for the integration of SDG 6 indicators within broader sustainability assessment frameworks that account for system interactions, trade-offs, and context-specific priorities (Van Leeuwen and Sjerps 2015). In Mediterranean regions, such integrated approaches are particularly important given the tight coupling between water availability, ecosystem services, infrastructure performance, and socio-economic conditions (Garrick et al. 2017; Grizzetti et al. 2016).

From fragmented indicators to integrated multi-dimensional assessment frameworks

Traditional sustainability assessments in the water sector have frequently focused on isolated performance dimensions, such as technical efficiency, water losses, or financial indicators, often overlooking broader environmental and social implications (Singh et al. 2012; Pires et al. 2017; Malagó et al. 2021a). While these approaches provide valuable insights, they are insufficient to support strategic decision-making in complex and dynamic contexts characterized by multiple objectives and competing priorities. This is even more relevant for public water and sanitation companies that are tied to political and social dynamics and have a service-led operation that in many cases is below market prices, which ends up adding constraints to the already complex decision-making scenario (Endo et al. 2017; Mekonnen and Hoekstra 2016).

Integrated assessment frameworks seek to overcome these limitations by combining diverse indicator domains within a coherent analytical structure (Malagó et al. 2021a). Such frameworks enable the simultaneous consideration of environmental footprints, ecosystem services, social responsibility, governance quality, and infrastructure resilience, thereby reflecting the multi-dimensional nature of sustainability in urban water systems (Grizzetti et al. 2016; Tiedmann et al. 2024).

Multi-Criteria Decision Analysis (MCDA) has emerged as a particularly suitable methodological approach for integrated sustainability assessment in the water sector, due to its ability to handle heterogeneous indicators, incorporate stakeholder preferences, and support transparent comparison across alternatives (Cinelli et al. 2014; Dolan et al. 2021). When combined with advanced visualization techniques, such as heatmaps, MCDA can further enhance the interpretability of results and facilitate communication with decision-makers (Malagó et al. 2021a; Liquete et al. 2013).

Research gap, objectives and contribution of the study

Although significant progress has been made in developing sustainability indicators and assessment frameworks for water utilities, important gaps remain. In particular, there is a lack of operational methodologies that integrate circular economy principles, water resilience considerations, and SDG 6–aligned indicators within a unified decision-support framework applicable at the utility level (Rodina 2019; Calleros-Islas 2012). Moreover, empirical applications of such integrated approaches to concrete sectors and organizations, especially in water-scarce Mediterranean contexts, remain limited.

This study addresses these gaps by proposing and applying an integrated multi-criteria framework for sustainability and circular economy assessment in public water utilities. The framework combines SDG 6–oriented indicators, environmental footprint analysis, ecosystem services assessment, infrastructure performance metrics, and backcasting analysis within an MCDA-based approach supported by heatmap visualization. The methodology is applied to two real public water utilities operating in a Mediterranean context characterized by recurrent water scarcity and increasing climate stress.

Working with public utilities is also meant to address a relevant gap in sustainability assessment, which is to incorporate the social dimension within the assessment since the design of the methods, with an operative and decision-oriented nature (Calleros-Islas 2012). The social dimension of sustainability is still commonly overseen or added as an afterthought, but in the case of public utilities it is more important that it is included to reflect the service-led instead of a profit-led management. This means that public utilities are, in a broad sense, more prone to include concrete and accessible governance and social legitimacy mechanisms, even if done to comply with current law and public policy frameworks (Caputo and Fasiello 2024).

Due to confidentiality constraints, critical infrastructure protection and in compliance with research ethics, the utilities where the methodology was tested are anonymized throughout the manuscript.

By linking circular water economy strategies with water resilience objectives, the study contributes to advancing operational tools for evidence-based planning and strategic decision-making in public water services. The proposed framework is designed to be adaptable and replicable, offering relevance for water utilities facing similar sustainability and resilience challenges in other regions.

2. Materials and methods

The proposed methodology is designed as an integrated assessment framework to evaluate sustainability, circularity, and water resilience in the water supply and sanitation sector, specifically in public water utilities. It combines indicator-based assessment with Multi-Criteria Decision Analysis (MCDA) and scenario-oriented backcasting to support strategic decision-making under conditions of uncertainty and water scarcity (Belton and Stewart 2002; Martín-López et al. 2014). The framework addresses the multi-dimensional nature of sustainability by integrating environmental, social, technical, economic and governance-related dimensions within a unified analytical structure (Malagó et al. 2021a).

The methodological workflow consists of six main steps: (i) selection and structuring of sustainability and circular economy indicators aligned with SDG 6; (ii) data collection and normalization; (iii) definition of evaluation criteria and weighting schemes; (iv) application of MCDA for integrated performance assessment; (v) visualization of results using heatmap-based representations; and (vi) backcasting analysis to explore strategic pathways towards enhanced circularity and water resilience. This stepwise approach ensures transparency, replicability, and adaptability to different utility contexts (Cinelli et al. 2014; Brunner and Rechberger 2016; Ellen MacArthur Foundation 2015; Maziotis and Molinos-Senante 2025a).

2.2. Case study selection and anonymization

The framework was applied to two public water utilities operating in urban Mediterranean contexts. The selected utilities are characterized by comparable regulatory and climatic conditions, while exhibiting differences in size, infrastructure characteristics, resource availability, operational practices, and governance arrangements (Maziotis and Molinos-Senante 2025b; Batty 2018). This contrast enables a meaningful comparative assessment while maintaining a consistent contextual background.

Due to confidentiality constraints, the identities of the utilities and the cities in which they operate are not disclosed. Throughout the manuscript, the case studies are referred to as Utility 1 and Utility 2. This anonymization approach also follows research ethics and is commonly adopted in applied sustainability research involving field-gathered operational data regarding critical infrastructures and resources (which include all water management facilities), and does not affect the validity or robustness of the comparative analysis.

System boundaries and operational scheme of the compared public water utilities

To support the comparative assessment developed in this study, Fig. 1 presents the operational and administrative system boundaries adopted for the two public water utilities analyzed. The figure synthesizes the main stages of the urban water cycle considered in the study and clarifies the input and output flows that were accounted in the integrated sustainability and circularity assessment (ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines n.d.; ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework n.d.; Arana-Landin and Heras-Saizarbitoria 2011).

As shown in Fig. 1, the system begins with catchment and adduction, where the main raw water sources enter the utilities, including surface water, groundwater, and rainwater. These flows are subsequently transferred to the treatment stage, which comprises the main potable water processes, namely coagulation, flocculation, filtration, and disinfection. Once treated, water enters the stages of storage and rechlorination. Finally, water is sent to distribution and consumption stages, where water is delivered to end users. The analysis also includes the wastewater treatment stage, covering conveyance, treatment and discharge, as well as a complementary component for system administration, associated with administrative water consumption and related indirect operational uses.

Figure 1 also identifies the main internal and external flows used to structure the analysis. The water to be treated (A) represents the raw water abstracted and conveyed into the treatment system; treated water (B) refers to the potable water transferred across storage, distribution, and final use stages; residual sludge (C) represents the main solid by-product generated during drinking water treatment; untreated wastewater / treated wastewater (D) represents the wastewater flows generated after consumption and managed within the sanitation system. This flow-based representation provides a common analytical structure for comparing both utilities under a shared system boundary.

The incorporation of this scheme is methodologically relevant because it shows which processes are included in the assessment and how the different material and water flows are connected throughout the service chain. In this way, Fig. 1 facilitates the interpretation of the indicators presented in the following sections and supports the comparability of the two case studies under a harmonized operational framework.

2.3. Indicator system design

SDG 6–oriented indicators

The indicator system was structured around SDG 6 – Clean Water and Sanitation, which provides a comprehensive framework for addressing water availability, quality, efficiency, ecosystem protection, and governance (Programme 2018; Gain et al. 2016). Indicators related to water-use efficiency, non-revenue water, service coverage, and water quality were selected to capture core operational and sustainability aspects relevant to public water utilities.

Given that SDG 6 indicators are primarily designed for national-level reporting, they were adapted to the utility scale following recommendations from previous studies on local SDG implementation (Allen et al. 2016k et al. 2016).

Environmental footprint indicators

Environmental performance was assessed using indicators related to water footprint and carbon footprint, reflecting both direct and indirect resource use and emissions associated with water service provision (Mekonnen and Hoekstra 2016; ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines n.d.). These indicators capture pressures on water resources and climate-related impacts, which are particularly relevant in Mediterranean water-scarce contexts (Mekonnen and Hoekstra 2016).

Ecosystem services indicators

To account for interactions between water services and natural systems, indicators related to ecosystem services were incorporated, focusing on regulating and supporting services such as water regulation, ecosystem integrity, and environmental flows (Grizzetti et al. 2016; Gómez-Baggethun and Barton 2013). This component allows the framework to move beyond purely technical performance and consider broader environmental sustainability implications.

Circular economy indicators

Circular economy indicators were included to evaluate the extent to which utilities adopt strategies related to resource efficiency, water reuse, energy recovery, and material valorization (Geissdoerfer et al. 2018; Van Der Hoek et al. 2016). These indicators reflect the operationalization of circular water economy principles at the utility level and their contribution to reducing linear resource flows.

Social responsibility and governance indicators

Social and governance dimensions were captured through indicators related to transparency, stakeholder engagement, occupational health and safety, customer communication, and institutional capacity (Ferguson et al. 2013). These aspects are increasingly recognized as critical enablers of sustainability transitions in public service provision (Allen et al. 2016).

Infrastructure and operational performance indicators

Infrastructure-related indicators addressed asset condition, operational robustness, and system efficiency, recognizing the role of infrastructure performance in both sustainability and resilience outcomes (Makropoulos and Butler 2010). These indicators are particularly relevant for assessing adaptive capacity under climate stress and demand variability.

Data collection, normalization and aggregation

Data for the selected indicators were obtained from operational records and internal monitoring systems of the utilities. To enable comparability across indicators with different units and scales, all indicator values were normalized using a min–max transformation, resulting in dimensionless scores ranging from 0 (lowest performance) to 1 (highest performance), following established practices in sustainability assessment (Singh et al. 2012; Pires et al. 2020; Blancas et al. 2010).

Normalized indicator scores were grouped into thematic categories corresponding to the main sustainability dimensions, allowing both disaggregated and aggregated analysis.

2.4. Multi-Criteria Decision Analysis (MCDA)

MCDA was employed as the core analytical tool to integrate heterogeneous indicators into a composite sustainability and circularity assessment (Cinelli et al. 2014). A weighted linear aggregation method was applied, enabling transparent combination of indicator scores while preserving interpretability.

Weights were assigned at the criteria level to reflect the relative importance of different sustainability dimensions. In the absence of stakeholder-derived weights, equal weighting was adopted as a baseline scenario, a common approach in exploratory sustainability assessments (Malagó et al. 2021a). Sensitivity analysis was conducted to assess the influence of alternative weighting schemes on the relative performance of the two utilities.

To enhance the interpretability and communicability of results, MCDA outputs were visualized using heatmap representations. Heatmaps enable intuitive comparison across utilities and sustainability dimensions by mapping performance scores to color gradients (Malagó et al. 2021b). This visual approach supports the identification of strengths, weaknesses, trade-offs, and complementarities between the two utilities, facilitating engagement with decision-makers and practitioners.

2.5. Backcasting analysis for circularity and water resilience pathways

Backcasting analysis was applied to explore strategic pathways towards enhanced circularity and water resilience (Robinson 1990; Quist and Vergragt 2006). Rather than projecting current trends forward, backcasting starts from desired future sustainability states and identifies actions and milestones required to achieve them.

In this study, backcasting was used to contextualize MCDA results within longer-term transition pathways, highlighting priority interventions and governance considerations for public water utilities operating under water-scarce conditions. This approach supports the integration of short-term performance assessment with long-term strategic planning (Butler et al. 2017; Makropoulos and Butler 2010).

Table 1 summarizes the main methodological steps of the proposed integrated assessment framework. The table highlights how diverse analytical components (ranging from indicator-based assessment and MCDA to heatmap visualization and backcasting) are combined to support sustainability, circularity, and water resilience assessment in public water utilities.

Table 1
Summary of the integrated methodological framework.

Step	Methodological component	Description	Main data source
01	Case study selection and anonymization	Selection of two real public water utilities operating in Mediterranean urban contexts; anonymization applied due to confidentiality constraints (Utility 1–2).	(Programme 2018)
02	Indicator system design	Development of a multi-dimensional indicator system aligned with SDG 6, covering environmental, circular economy, ecosystem services, social, governance, and infrastructure dimensions	(Programme 2018; Gain et al. 2016k et al. 2016)
03	Environmental footprint assessment	Assessment of water and carbon footprints to capture resource use and climate-related impacts of water service provision.	(Mekonnen and Hoekstra 2016; ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines n.d.)
04	Ecosystem services assessment	Inclusion of ecosystem service indicators related to water regulation, environmental flows, and ecosystem integrity.	(Grizzetti et al. 2016; Gómez-Baggethun and Barton 2013)
05	Circular economy assessment	Evaluation of circular water economy strategies, including resource efficiency, water reuse, energy recovery, and material valorization.	(Geissdoerfer et al. 2018; van der Hoek 2012)
06	Social responsibility and governance assessment	Analysis of transparency, stakeholder engagement, occupational safety, and institutional capacity indicators.	(Ferguson et al. 2013)
07	Infrastructure and operational performance	Assessment of infrastructure condition, system efficiency, and operational robustness relevant for sustainability and resilience.	(Makropoulos and Butler 2010; Butler et al. 2017)
08	Data normalization and aggregation	Normalization of indicators using min–max scaling to ensure comparability across heterogeneous metrics.	(Singh et al. 2012; Pires et al. 2020)
09	Multi-Criteria Decision Analysis	Integration of indicators using weighted linear aggregation; baseline equal weighting and sensitivity analysis applied.	(Cinelli et al. 2014; Malagó et al. 2021a)

Step	Methodological component	Description	Main data source
10	Heatmap-based visualization	Visual representation of MCDA results using heatmaps to support comparative analysis and interpretability.	(Malagó et al. 2021a)
11	Backcasting analysis	Exploration of long-term circularity and water resilience pathways starting from desired future states.	(Robinson 1990; Quist and Vergragt 2006; Butler et al. 2017)

Source: Prepared by the author based on the literature review.

3. Results

3.1. SDG 6 performance across the two public water utilities

The SDG 6–oriented assessment reveals differentiated performance profiles across the two public water utilities, reflecting variations in operational practices, infrastructure characteristics, and management approaches within a shared Mediterranean context. Figure 2 presents the comparative performance of the two anonymized utilities across selected SDG 6–related dimensions, including water-use efficiency, service quality and reliability, and governance and access. The heatmap highlights contrasts in operational efficiency and governance-related performance, illustrating how SDG 6 indicators capture core aspects of water service provision while revealing heterogeneous performance profiles.

The heatmap illustrates differentiated performance across key SDG 6 dimensions, highlighting stronger efficiency- and reliability-related performance for Utility 1 and comparatively higher governance- and access-related performance for Utility 2.

Overall, Utility 1 exhibits comparatively stronger performance in indicators related to water-use efficiency and service reliability, suggesting effective operational control and demand management practices. Utility 2 shows a more balanced but moderately lower performance across most SDG 6 dimensions, particularly in efficiency-related indicators. These results illustrate the added value of using SDG 6 as a structured reference framework, while also highlighting the need to complement SDG indicators with additional dimensions to capture circularity and resilience aspects more comprehensively.

3.2. Environmental performance: water and carbon footprint

Environmental footprint analysis provides further insight into the sustainability performance of the utilities beyond SDG 6 indicators. Figure 3 summarizes the environmental footprint performance of the two utilities, focusing on operational water footprint, energy-related emissions, and system losses. The

heatmap representation enables an integrated comparison of direct and indirect environmental pressures associated with water service provision, complementing efficiency-oriented SDG 6 indicators.

The values shown in the heatmap correspond to normalized comparative performance scores, with higher values indicating better environmental performance.

Utility 1 achieves consistently higher scores across all three dimensions (0.79, 0.76, and 0.74), indicating lower relative environmental pressure per unit of service delivered. By contrast, Utility 2 records lower scores (0.63, 0.60, and 0.58), reflecting comparatively higher water footprint intensity, greater energy-related emissions, and a less favorable losses profile. These differences are likely associated with variations in operational efficiency, energy use, pumping requirements, and infrastructure characteristics.

The results confirm the value of integrating footprint indicators into sustainability assessments, as they capture indirect environmental pressures not fully represented by conventional efficiency metrics.

3.3. Ecosystem services assessment

The ecosystem services assessment reveals clear differences in the extent to which water service operations are aligned with environmental protection and ecosystem integrity objectives.

Figure 4 illustrates the performance of the two utilities with respect to ecosystem services–related indicators, including environmental flows, ecosystem protection, and territorial integration. Utility 2 performs relatively well in indicators related to ecosystem protection and environmental flows, suggesting stronger integration of these considerations within operational and planning processes. Utility 1 displays more moderate performance in ecosystem service indicators, indicating potential opportunities to strengthen ecosystem-based management practices.

These results point towards the relevance of including ecosystem services indicators in sustainability assessments. This is particularly relevant in water-scarce Mediterranean regions where ecological pressures are significant.

The heatmap compares normalized performance scores for environmental flows, ecosystem protection, and territorial integration. Results indicate stronger ecosystem-related performance for Utility 2, suggesting greater alignment with ecosystem-based management objectives.

3.4. Comparative performance across circularity, governance, and infrastructure dimensions

The comparative assessment of circularity, governance, and infrastructure performance reveals that the two anonymized public water utilities show distinct and non-linear sustainability profiles. Rather than converging toward a single pattern of performance, the results suggest that each utility combines specific strengths and weaknesses across these complementary dimensions. This finding is particularly relevant from an analytical perspective, as it confirms that sustainability performance in public water services cannot be adequately captured through isolated technical or environmental indicators alone.

Instead, it requires an integrated perspective capable of simultaneously accounting for organizational, operational, and circularity-related dynamics.

In relation to circular economy performance, the comparison points to differentiated patterns of maturity and implementation. Utility 2 appears to perform more favourably in aspects associated with resource efficiency, reuse practices, and the valorization of internal flows, suggesting a stronger orientation towards applied circularity strategies. By contrast, Utility 1 shows a more moderate but still consistent circular economy profile. Importantly, these differences should not be interpreted only in terms of the number of indicators considered, as both utilities show a similar degree of coverage in the assessment framework. As summarized in Table 2, Utility 1 incorporated 18 circular economy indicators and achieved full circular value chain coverage, whereas Utility 2 incorporated 17 indicators and achieved a partial coverage. This indicates that the comparatively stronger circularity profile of Utility 2 is less a function of broader scope and more of a favorable performance in the implementation of the strategies. In this sense, the results suggest that the depth and effectiveness of circular practices may be more decisive than the extensiveness of its formal coverage alone.

A similar pattern is observed in the governance and social responsibility dimension. The results indicate that Utility 2 performs comparatively better in aspects related to transparency, stakeholder engagement, and institutional capacity. This points to a governance configuration that is more conducive to the implementation of circularity strategies. Utility 1 also demonstrates a robust governance profile; however, its comparative performance appears somewhat less pronounced in these enabling dimensions.

Moreover, the evidence summarized in Table 2 introduces an important qualification to this interpretation, as Utility 1 is characterized by a higher level of sustainability communication mechanisms, whereas Utility 2 is classified at a medium level. This highlights the importance of understanding governance not as a single-variable attribute, but as a multidimensional and internally differentiated category, where its elements – institutional strength, stakeholder interaction and communication capacity –, do not necessarily evolve in parallel. Accordingly, the results suggest that both utilities possess governance-related assets that are expressed through different organizational configurations.

The clearest differentiation between the two cases is observed in the dimension of infrastructure performance and operational robustness. Here, Utility 1 demonstrates a more favourable profile, particularly in relation to infrastructure condition, asset performance, and operational efficiency. This result is consistent with the characterization presented in Table 2, where Utility 1 is classified as robust and Utility 2 as intermediate in the infrastructure and asset performance assessment.

From a resilience perspective, this finding is especially significant, as it suggests that Utility 1 currently benefits from a stronger technical and operational base capable of supporting service reliability under existing conditions and, potentially, greater adaptive capacity under future stress scenarios. Utility 2, although comparatively stronger in circularity and governance-related dimensions, appears to face

greater limitations in infrastructural robustness, which may constrain the long-term consolidation of its sustainability performance if not addressed through targeted investment and operational reinforcement.

These results demonstrate that the two utilities do not occupy fixed positions within a simple hierarchy of sustainability performance. Instead, they reflect contrasting but internally coherent performance profiles. Utility 1 is characterized by stronger infrastructure robustness and more stable operational performance, while Utility 2 shows greater comparative strength in circular economy implementation and several governance-related dimensions. This distinction is important because it reinforces the value of multidimensional assessment frameworks – such as the one developed in this study. More specifically, it shows that high performance in one dimension does not automatically translate into superiority across the whole system, and that meaningful comparison requires attention to the trade-offs and complementarities that emerge between technical, organizational, and circularity-oriented criteria.

A broader interpretation of these findings helps explain why the overall comparative assessment cannot be reduced to environmental footprint metrics or to SDG 6-related efficiency indicators alone. The differentiated profiles observed across circularity, governance and infrastructure dimensions suggest that sustainability and water resilience are shaped by the interaction of enabling institutional conditions, resource management strategies, and the material robustness of service provision systems. Therefore, these dimensions should be understood not as secondary complements to the assessment, but as constitutive elements of utility performance under a circular and resilience-oriented perspective.

3.5. Integrated MCDA results and comparative analysis

The integrated MCDA results, synthesized in Fig. 5, present the aggregated outcomes of the Multi-Criteria Decision Analysis, combining environmental, circular economy, governance, and infrastructure dimensions. The heatmap enables a synthetic comparison of overall sustainability and circularity performance across the two utilities, highlighting trade-offs and complementarities between dimensions.

The figure presents normalized comparative scores for environmental, circular economy, governance, and infrastructure dimensions, together with the overall MCDA score. Results highlight trade-offs and complementarities across dimensions: Utility 1 achieves the higher overall score, mainly driven by stronger environmental and infrastructure performance, whereas Utility 2 performs better in circular economy and governance-related dimensions.

Utility 1 achieves the higher overall MCDA score, driven primarily by strong operational efficiency and infrastructure performance. Utility 2 attains a slightly lower overall score, supported by stronger circular economy and governance-related performance.

Importantly, the integrated assessment highlights trade-offs between dimensions, illustrating that higher performance in one area does not automatically translate into overall sustainability or resilience. These findings provide a robust empirical basis for the subsequent discussion on the role of integrated assessment frameworks in supporting strategic decision-making for public water utilities.

Table 2 reports selected quantitative and qualitative indicators commonly used in sustainability assessment studies to complement the aggregated MCDA results. Quantitative indicators are expressed using relative units (e.g., per employee) to ensure comparability across utilities and preserve confidentiality. When exact numerical values are not directly comparable across cases, structured qualitative categories are applied. This approach enhances empirical transparency while maintaining analytical robustness and confidentiality.

Table 2
Selected quantitative sustainability and circular economy indicators across the two anonymized utilities.

Assessment dimension	**Indicator**	**Unit / scale**	**Utility 1**	**Utility 2**
Environment & SDG 6	SDG 6–aligned indicators assessed	Number	25	31
Carbon footprint	GHG emissions per employee	t CO_2-eq / employee * year	9.97	22.25
Water footprint	Water footprint per employee	M^3 / employee * year	39	0.74
Circular economy	Circular economy indicators assessed	Number	18	17
	Circular value chain coverage (raw materials → recycling)	Qualitative	Full	Partial
Ecosystem services	Ecosystem services assessment framework	Qualitative	Applied	Applied
	Territorial impact neutrality approach	Qualitative	Yes	Partial
Communication & governance	Sustainability communication mechanisms	Qualitative	High	Medium
Infrastructure	Infrastructure and asset performance assessment	Qualitative	Robust	Intermediate

Source: Prepared by the author.

Table 2 provides selected quantitative and qualitative indicators to contextualize and support the aggregated MCDA results. The indicators highlight contrasting sustainability profiles across the two utilities, with Utility 1 exhibiting stronger performance in operational efficiency and infrastructure robustness, while Utility 2 demonstrates higher maturity in circular economy implementation, ecosystem services integration, and governance-related dimensions. This complementary evidence reinforces the value of combining indicator-based analysis with MCDA and heatmap visualization to capture multi-dimensional sustainability and resilience patterns.

4. Discussion

The results confirm the relevance of integrated multi-criteria frameworks for capturing the multi-dimensional nature of sustainability, circular economy, and water resilience in public water utilities. By combining SDG 6–oriented indicators with environmental footprints, ecosystem services, governance, and infrastructure performance within an MCDA-based structure, the proposed framework overcomes limitations associated with fragmented or single-dimension assessments commonly applied in the water sector (Singh et al. 2012k et al. 2016).

The comparative analysis of the two utilities demonstrates that sustainability performance cannot be adequately characterized through isolated efficiency metrics alone. Instead, the results reveal differentiated sustainability profiles shaped by trade-offs between operational efficiency, environmental pressures, circular economy maturity, governance arrangements, and infrastructure robustness. This finding aligns with recent studies emphasizing the need for integrated assessment approaches capable of reflecting system-wide interactions and competing objectives in urban water systems (Malagó et al. 2021a; Morató Farreras et al. 2023).

Importantly, the MCDA framework enables transparent aggregation of heterogeneous indicators while preserving interpretability through heatmap visualization. This dual analytical–visual approach supports not only comparative assessment but also communication with decision-makers, addressing a critical gap identified in applied sustainability research for public utilities (Cinelli et al. 2014).

Interpreting trade-offs between efficiency, circularity, and governance

The results highlight clear trade-offs between sustainability dimensions, particularly between operational efficiency, circular economy performance, and governance-related factors. Utility 1 achieves higher overall MCDA scores driven primarily by strong infrastructure condition and operational efficiency, reflecting effective asset management and service reliability. In contrast, Utility 2 demonstrates stronger performance in circular economy and governance dimensions, including ecosystem services integration and strategic alignment with sustainability objectives.

These contrasting profiles illustrate that higher efficiency or infrastructure robustness does not automatically translate into superior circularity or environmental integration. This finding reinforces arguments in the literature that sustainability transitions in the water sector require coordinated progress across technical, organizational, and institutional dimensions rather than isolated optimization of individual performance indicators (Korhonen et al. 2018; Rodina 2019).

The governance-related strengths observed in Utility 2 appear to play an enabling role in advancing circular economy practices and ecosystem-based management, even where infrastructure-related performance is comparatively lower. This supports previous research highlighting governance capacity, stakeholder engagement, and institutional coherence as key drivers of sustainability and resilience in public water services (Allen et al. 2016).

Complementarity of SDG 6 indicators and extended sustainability dimensions

While SDG 6 provides a robust and widely recognized framework for assessing water-related sustainability, the results demonstrate its limitations when applied in isolation at the utility level. SDG 6 indicators effectively capture core aspects of service provision, such as efficiency, reliability, and access, but are less sensitive to circular economy practices, indirect environmental pressures, and ecosystem service interactions.

By complementing SDG 6–oriented indicators with environmental footprint analysis, ecosystem services assessment, and circular economy metrics, the proposed framework provides a more comprehensive representation of sustainability performance. This integrated approach responds directly to calls in the literature for adapting and extending SDG indicators to support decision-making at sub-national and organizational scales (Van Leeuwen and Sjerps 2015; Nilsson et al. 2016).

The findings suggest that such hybrid indicator systems are particularly relevant in water-scarce Mediterranean contexts, where sustainability outcomes are tightly coupled with ecological conditions, long-term infrastructure performance, and governance arrangements. This reinforces the importance of context-specific assessment frameworks that move beyond standardized indicator reporting (Grizzetti et al. 2016; Garrick et al. 2017).

Implications for strategic decision-making and water resilience

The integration of MCDA with backcasting analysis enhances the strategic relevance of the framework by linking current performance profiles with long-term transition pathways. Rather than ranking utilities in a static manner, the framework supports identification of priority intervention areas and potential leverage points for improving sustainability and water resilience.

For example, the results suggest that utilities with strong operational efficiency and infrastructure performance may benefit from targeted investments in governance mechanisms and circular economy initiatives to enhance long-term resilience. Conversely, utilities exhibiting higher circularity and governance maturity may need to address infrastructure vulnerabilities to ensure robustness under increasing climate stress.

These insights align with emerging perspectives on water resilience that emphasize adaptive capacity, diversity of strategies, and long-term system robustness rather than short-term efficiency gains alone (Butler et al. 2017). The framework thus offers practical value for public water utilities seeking to balance immediate operational priorities with longer-term sustainability and resilience objectives.

Methodological limitations and future research directions

As with any applied sustainability assessment, the proposed framework has limitations that warrant consideration. First, the analysis relies on data derived from internal operational and sustainability assessments, which may vary in scope, resolution, and methodological detail across utilities. While normalization and anonymization procedures were applied to ensure comparability, some degree of contextual specificity is unavoidable.

Second, the weighting scheme adopted in the MCDA was based on equal weighting in the absence of clear stakeholder-derived preferences. Although sensitivity analysis suggests that the main comparative patterns are robust, future applications could benefit from participatory weighting processes involving utility managers, regulators, and other stakeholders.

Finally, the empirical application focuses on two utilities operating within a shared Mediterranean context. While this enhances internal consistency and depth of analysis, further applications across a broader range of institutional and climatic contexts would strengthen the framework and support its refinement.

Future research could explore dynamic extensions of the framework, incorporating temporal analysis, stress testing in specific scenarios, or integration with digital decision-support tools to further enhance its applicability in rapidly evolving water management contexts.

5. Conclusions

This study proposed and applied an integrated multi-criteria framework for assessing sustainability, circular economy, and water resilience in public water utilities operating in water-scarce Mediterranean contexts. By combining SDG 6–oriented indicators with environmental footprint analysis, ecosystem services assessment, governance and infrastructure performance metrics, and backcasting within a Multi-Criteria Decision Analysis (MCDA) approach, the framework addresses key limitations of fragmented sustainability assessments commonly used in the water sector.

The empirical application to two anonymized public water utilities demonstrates that sustainability performance is inherently multi-dimensional and shaped by trade-offs between efficiency, circularity, governance, and infrastructure robustness. The results show that strong operational efficiency and infrastructure condition do not necessarily coincide with higher circular economy maturity or ecosystem integration, underscoring the importance of integrated assessment approaches capable of capturing complementary and sometimes competing sustainability dimensions.

The use of heatmap-based visualization in combination with MCDA proved particularly effective in enhancing the interpretability and communicability of results. This visual–analytical integration supports transparent comparison, facilitates engagement with decision-makers, and strengthens the operational relevance of sustainability assessments at the utility level. Moreover, the incorporation of backcasting analysis links current performance profiles with long-term transition pathways, enabling utilities to identify strategic priorities and leverage points for enhancing resilience under increasing climate stress and resource constraints.

From a practical perspective, the proposed framework offers a replicable and adaptable decision-support tool for public water utilities seeking to operationalize sustainability, circularity, and resilience objectives within their planning and management processes. Its modular structure allows adaptation to different institutional, regulatory, and climatic contexts, while preserving methodological consistency.

Future research should focus on expanding empirical applications across a wider range of contexts, integrating participatory weighting and stakeholder engagement processes, and exploring dynamic extensions of the framework through temporal analysis and scenario-based assessments. Such developments would further strengthen the contribution of integrated multi-criteria approaches to evidence-based decision-making in the water sector.

Declarations

Competing interests

The authors declare that this study was based on analyses conducted with financial support from the two anonymized public water utilities assessed in the manuscript. The identities of the utilities are withheld for confidentiality reasons. The funders had no role in the interpretation of the comparative results, the writing of the manuscript, or the decision to submit the article for publication.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality restrictions associated with operational data from anonymized public water utilities and critical infrastructure protection requirements. Aggregated data may be available from the corresponding author on reasonable request.

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Author contributions

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Writing – review and editing: all authors. Supervision: Jordi Morató Farreras.

All authors read and approved the final manuscript.

References

1. Albrecht TR, Crootof A, Scott CA (2018) The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. Environ Res Lett 13(4):043002. https://doi.org/10.1088/1748-9326/AAA9C6
2. Allen C, Metternicht G, Wiedmann T (2016) National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. Environ Sci Policy 66:199–207. https://doi.org/10.1016/j.envsci.2016.09.008
3. Arana-Landin G, Heras-Saizarbitoria I (2011) Paving the way for the ISO 14006 ecodesign standard: an exploratory study in Spanish companies. Clean Prod 19:1007–1015
4. Bach PM, Rauch W, Mikkelsen PS, McCarthy DT, Deletic A (2014) A critical review of integrated urban water modelling – Urban drainage and beyond. Environ Model Softw 54:88–107. https://doi.org/10.1016/J.ENVSOFT.2013.12.018
5. Batty M (2018) Digital twins. Environ Plann B: Urban Analytics City Sci 45(5):817–820. https://doi.org/10.1177/2399808318796416
6. Belton V, Stewart TJ (2002) Multiple Criteria Decision Analysis. Multiple Criteria Decis Anal. https://doi.org/10.1007/978-1-4615-1495-4
7. Blancas FJ, González M, Lozano-Oyola M, Pérez F (2010) The assessment of sustainable tourism: Application to Spanish coastal destinations. Ecol Ind 10(2):484–492. https://doi.org/10.1016/J.ECOLIND.2009.08.001
8. Brunner PH, Rechberger H (2016) Practical handbook of material flow analysis. Practical Handb Mater Flow Anal 1–318. https://doi.org/10.1007/BF02979426
9. Butler D, Ward S, Sweetapple C, Astaraie-Imani M, Diao K, Farmani R, Fu G (2017) Reliable, resilient and sustainable water management: the Safe & SuRe approach. Global Challenges 1(1):63–77. https://doi.org/10.1002/GCH2.1010
10. Calleros-Islas A (2012), December Sustainability Frameworks: their influence on the operational capacity of sustainability. *Sostenibilidad, Tecnologia y Humanismo*, 18. https://discovery.upc.edu/iii/encore/record/C__Rx1126613__Salejandra calleros islas__Orightresult__U__X2?lang = cat&suite = def
11. Caputo F, Fasiello R (2024) Environmental, social, and governance (ESG) reporting and accountability in the utilities sector: Research paths and policy directions. Utilities Policy 91:101847. https://doi.org/10.1016/J.JUP.2024.101847
12. Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol Ind 46:138–148. https://doi.org/10.1016/J.ECOLIND.2014.06.011
13. D'Amato D, Korhonen J, Toppinen A (2019) Circular, Green, and Bio Economy: How Do Companies in Land-Use Intensive Sectors Align with Sustainability Concepts? *Ecological Economics*, *158*(December 2018), 116–133. https://doi.org/10.1016/j.ecolecon.2018.12.026

14. Dolan F, Lamontagne J, Link R, Hejazi M, Reed P, Edmonds J (2021) Evaluating the economic impact of water scarcity in a changing world. Nat Commun 12(1). https://doi.org/10.1038/S41467-021-22194-0
15. Ellen MacArthur Foundation (2015) Growth within: a circular economy vision for a competitive Europe. Ellen MacArthur Foundation. Ed.). https://ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe
16. Endo A, Tsurita I, Burnett K, Orencio PM (2017) A review of the current state of research on the water, energy, and food nexus. J Hydrology: Reg Stud 11:20–30. https://doi.org/10.1016/J.EJRH.2015.11.010
17. Ferguson BC, Brown RR, Frantzeskaki N, de Haan FJ, Deletic A (2013) The enabling institutional context for integrated water management: Lessons from Melbourne. Water Res 47(20):7300–7314. https://doi.org/10.1016/J.WATRES.2013.09.045
18. Gain AK, Giupponi C, Wada Y (2016) Measuring global water security towards sustainable development goals. Environ Res Lett 11(12). https://doi.org/10.1088/1748-9326/11/12/124015
19. Garrick DE, Hall JW, Dobson A, Damania R, Grafton RQ, Hope R, Hepburn C, Bark R, Boltz F, De Stefano L, O'Donnell E, Matthews N, Money A (2017) Valuing water for sustainable development. Science 358(6366):1003–1005. https://doi.org/10.1126/SCIENCE.AAO4942
20. Geissdoerfer M, Vladimirova D, Evans S (2018) Sustainable business model innovation: A review. J Clean Prod 198:401–416. https://doi.org/10.1016/j.jclepro.2018.06.240
21. Gómez-Baggethun E, Barton DN (2013) Classifying and valuing ecosystem services for urban planning. Ecol Econ 86:235–245. https://doi.org/10.1016/J.ECOLECON.2012.08.019
22. Grizzetti B, Lanzanova D, Liquete C, Reynaud A, Cardoso AC (2016) Assessing water ecosystem services for water resource management. Environ Sci Policy 61:194–203. https://doi.org/10.1016/J.ENVSCI.2016.04.008
23. Hák T, Janoušková S, Moldan B (2016) Sustainable Development Goals: A need for relevant indicators. Ecol Ind 60:565–573. https://doi.org/10.1016/j.ecolind.2015.08.003
24. *ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework*. (n.d.). Retrieved March 9, (2026) from https://www.iso.org/standard/37456.html
25. *ISO 14046:2014 - Environmental management — Water footprint — Principles, requirements and guidelines*. (n.d.). Retrieved March 9, (2026) from https://www.iso.org/standard/43263.html
26. Joss S, Cook M, Dayot Y (2017) Smart Cities: Towards a New Citizenship Regime? A Discourse Analysis of the British Smart City Standard. J Urban Technol 24(4):29–49. https://doi.org/10.1080/10630732.2017.1336027
27. Kallis G (2010) Coevolution in water resource development: The vicious cycle of water supply and demand in Athens, Greece. Ecol Econ 69(4):796–809. https://doi.org/10.1016/J.ECOLECON.2008.07.025
28. Korhonen J, Honkasalo A, Seppälä J (2018) Circular Economy: The Concept and its Limitations. Ecol Econ 143:37–46. https://doi.org/10.1016/J.ECOLECON.2017.06.041

29. Liquete C, Piroddi C, Drakou EG, Gurney L, Katsanevakis S, Charef A, Egoh B (2013) Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. PLoS ONE 8(7):e67737. https://doi.org/10.1371/journal.pone.0067737
30. Makropoulos CK, Butler D (2010) Distributed water infrastructure for sustainable communities. Water Resour Manage 24(11):2795–2816. https://doi.org/10.1007/S11269-010-9580-5/METRICS
31. Malagó A, Comero S, Bouraoui F, Kazezyılmaz-Alhan CM, Gawlik BM, Easton P, Laspidou C (2021a) An analytical framework to assess SDG targets within the context of WEFE nexus in the Mediterranean region. Resour Conserv Recycl 164:105205. https://doi.org/10.1016/J.RESCONREC.2020.105205
32. Malagó A, Comero S, Bouraoui F, Kazezyılmaz-Alhan CM, Gawlik BM, Easton P, Laspidou C (2021b) An analytical framework to assess SDG targets within the context of WEFE nexus in the Mediterranean region. Resour Conserv Recycl 164:105205. https://doi.org/10.1016/J.RESCONREC.2020.105205
33. Mannina G, Gulhan H, Ni BJ (2022) Water reuse from wastewater treatment: The transition towards circular economy in the water sector. *Bioresource Technology*, *363*. https://doi.org/10.1016/J.BIORTECH.2022.127951
34. Martín-López B, Gómez-Baggethun E, García-Llorente M, Montes C (2014) Trade-offs across value-domains in ecosystem services assessment. Ecol Ind 37:220–228. PART Ahttps://doi.org/10.1016/J.ECOLIND.2013.03.003
35. Maziotis A, Molinos-Senante M (2025a) Assessing the resilience of water and wastewater utilities: A multi-criteria approach for Chile. *Socio-Economic Planning Sciences*, *102*. https://doi.org/10.1016/J.SEPS.2025.102340
36. Maziotis A, Molinos-Senante M (2025b) Evaluating the Sustainability of Water and Sanitation Services: A Comparative Analysis of Methodological Approaches. Sustain Dev 33(5):7038–7052. https://doi.org/10.1002/SD.3511
37. Mekonnen MM, Hoekstra AY (2016) Sustainability: Four billion people facing severe water scarcity. Sci Adv 2(2). https://doi.org/10.1126/SCIADV.1500323
38. Morató Farreras J, Jiménez LM, Garcia P, Sánchez GL, Santander OL, Escobedo V, de la Cruz B, Martí JL, Pérez C, Lagüela E, Pereira S, Pernas García JJ, Larruga S, Martínez FJ, J., Tollin N (2023) *Informe COTEC 2023: situación y evolución de la economía circular en España*. https://hdl.handle.net/2117/402119
39. Nika CE, Vasilaki V, Expósito A, Katsou E (2020) Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems. Water Res 187:116423. https://doi.org/10.1016/J.WATRES.2020.116423
40. Nilsson M, Griggs D, Visbeck M (2016) Policy: Map the interactions between Sustainable Development Goals. Nat 2016 534(7607):320–322. https://doi.org/10.1038/534320a. *534*
41. Pires A, Morato J, Peixoto H, Botero V, Zuluaga L, Figueroa A (2017) Sustainability Assessment of indicators for integrated water resources management. Sci Total Environ 578:139–147.

https://doi.org/10.1016/J.SCITOTENV.2016.10.217

42. Pires A, Morato J, Peixoto H, Bradley S, Muller A (2020) Synthesizing and standardizing criteria for the evaluation of sustainability indicators in the water sector. Environ Dev Sustain 22(7):6671–6689. https://doi.org/10.1007/S10668-019-00508-Z/METRICS
43. Programme authorCorporate:UNESCOWWA (2018) The United Nations world water development report 2018: nature-based solutions for water. UN Water Rep, 154. https://unesdoc.unesco.org/ark:/48223/pf0000261424
44. Quist J, Vergragt P (2006) Past and future of backcasting: The shift to stakeholder participation and a proposal for a methodological framework. Futures 38(9):1027–1045. https://doi.org/10.1016/J.FUTURES.2006.02.010
45. Robinson JB (1990) Futures under glass: A recipe for people who hate to predict. Futures 22(8):820–842. https://doi.org/10.1016/0016-3287(90)90018-D
46. Rodina L (2019) Defining water resilience: Debates, concepts, approaches, and gaps. Wiley Interdisciplinary Reviews: Water 6(2):e1334. https://doi.org/10.1002/WAT2.1334
47. Singh RK, Murty HR, Gupta SK, Dikshit AK (2012) An overview of sustainability assessment methodologies. Ecol Ind 15(1):281–299. https://doi.org/10.1016/J.ECOLIND.2011.01.007
48. Tiedmann HR, Sela L, Stephens KK, Faust KM (2024) Leveraging water utility customer reporting for resilient operations and management. Sustainable Cities Soc 101:105087. https://doi.org/10.1016/J.SCS.2023.105087
49. van der Hoek JP (2012) Towards a climate neutral water cycle. J Water Clim Change 3(3):163–170. https://doi.org/10.2166/WCC.2012.015
50. Van Der Hoek JP, De Fooij H, Struker A (2016) Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater. Resour Conserv Recycl 113:53–64. https://doi.org/10.1016/J.RESCONREC.2016.05.012
51. Van Leeuwen CJ, Sjerps RMA (2015) The City Blueprint of Amsterdam: An assessment of integrated water resources management in the capital of the Netherlands. Water Sci Technology: Water Supply 15(2):404–410. https://doi.org/10.2166/WS.2014.127

Figures

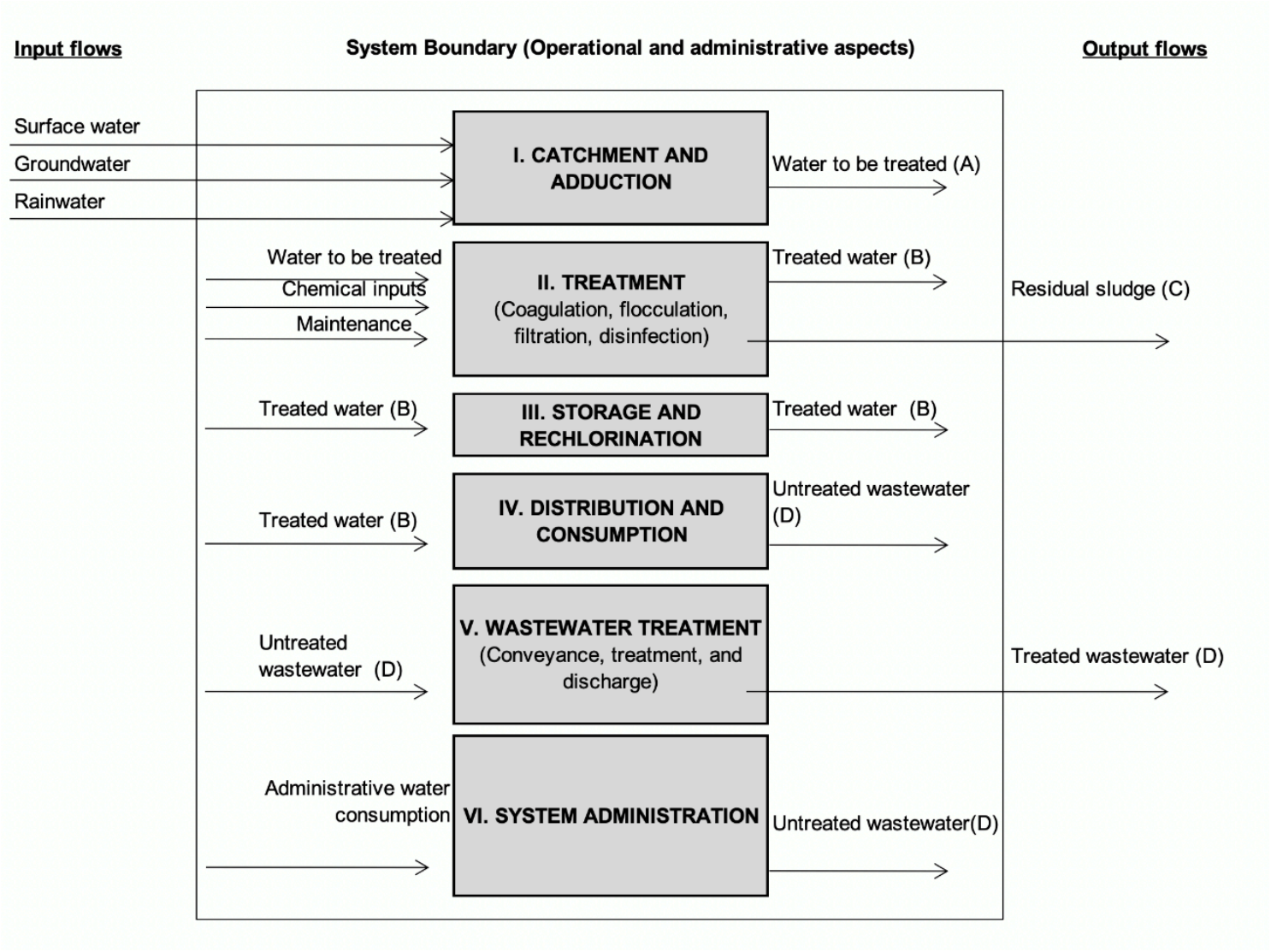


Figure 1

Operational and administrative system boundaries and main water flow scheme of the two compared public water utilities

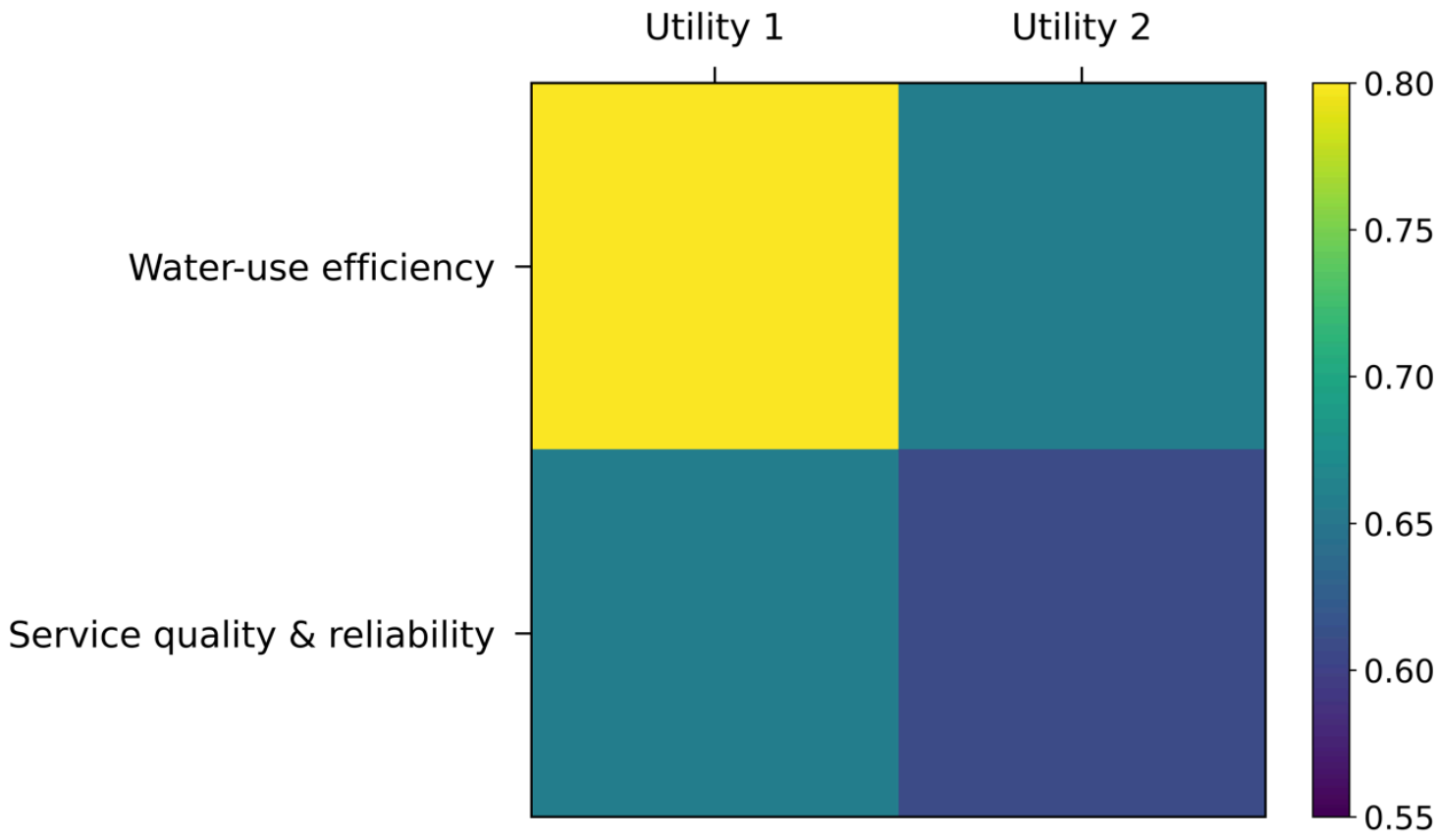


Figure 2

SDG 6–oriented performance comparison between two anonymized public water utilities. Prepared by the author.

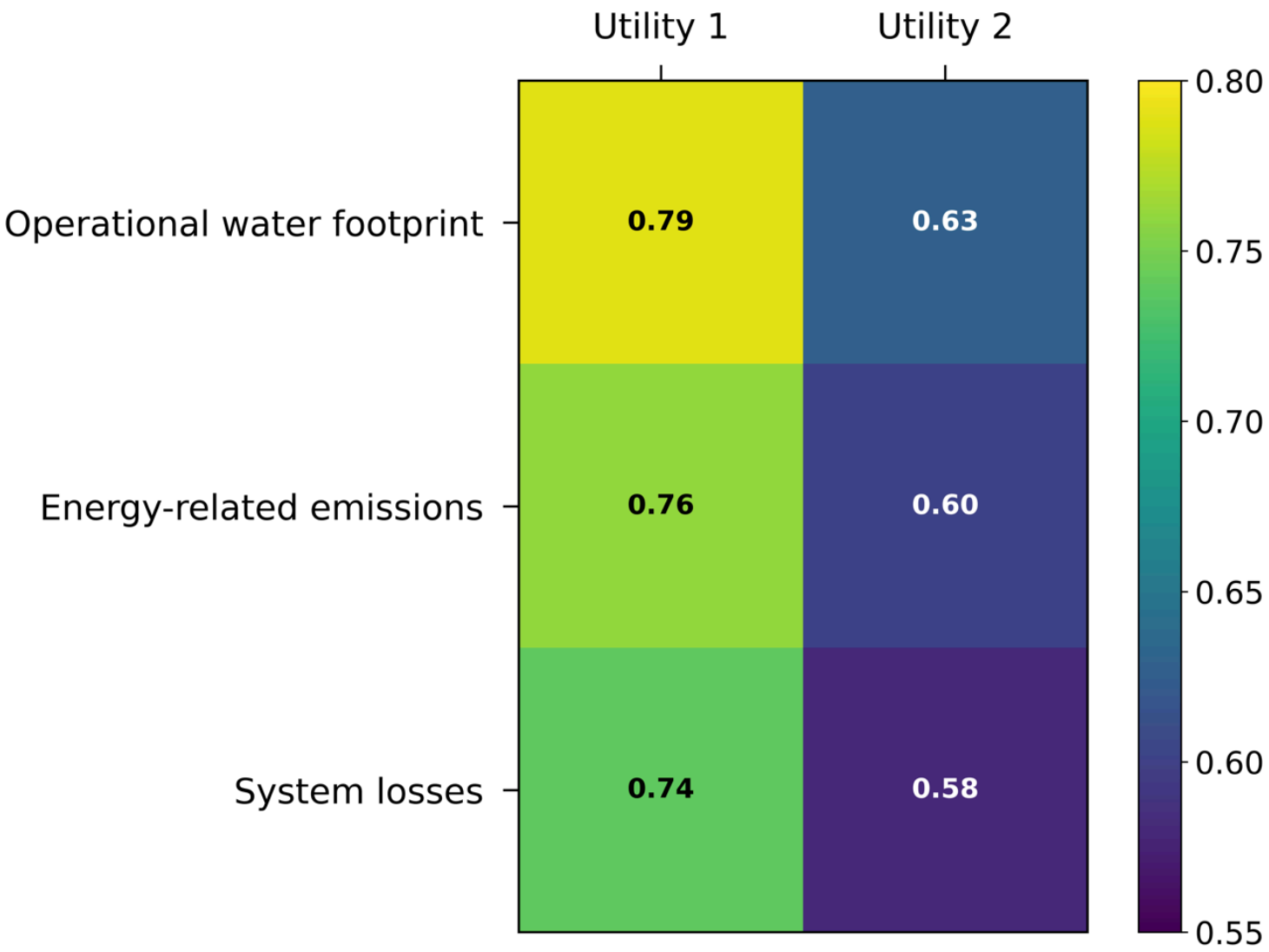


Figure 3

Comparative environmental footprint performance of two anonymized public water utilities. Prepared by the author.

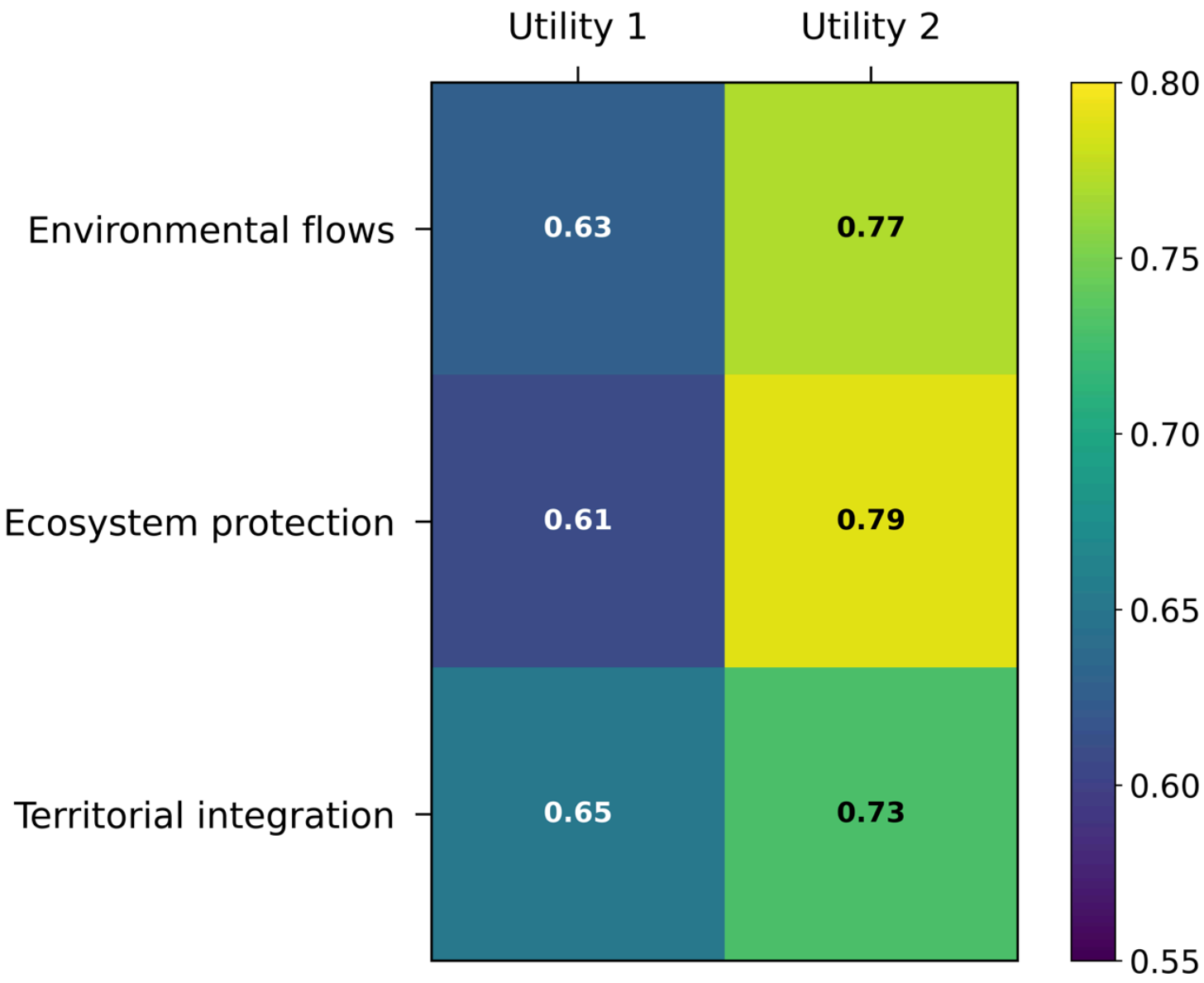


Figure 4

Ecosystem services–related performance of two anonymized public water utilities. Prepared by the author

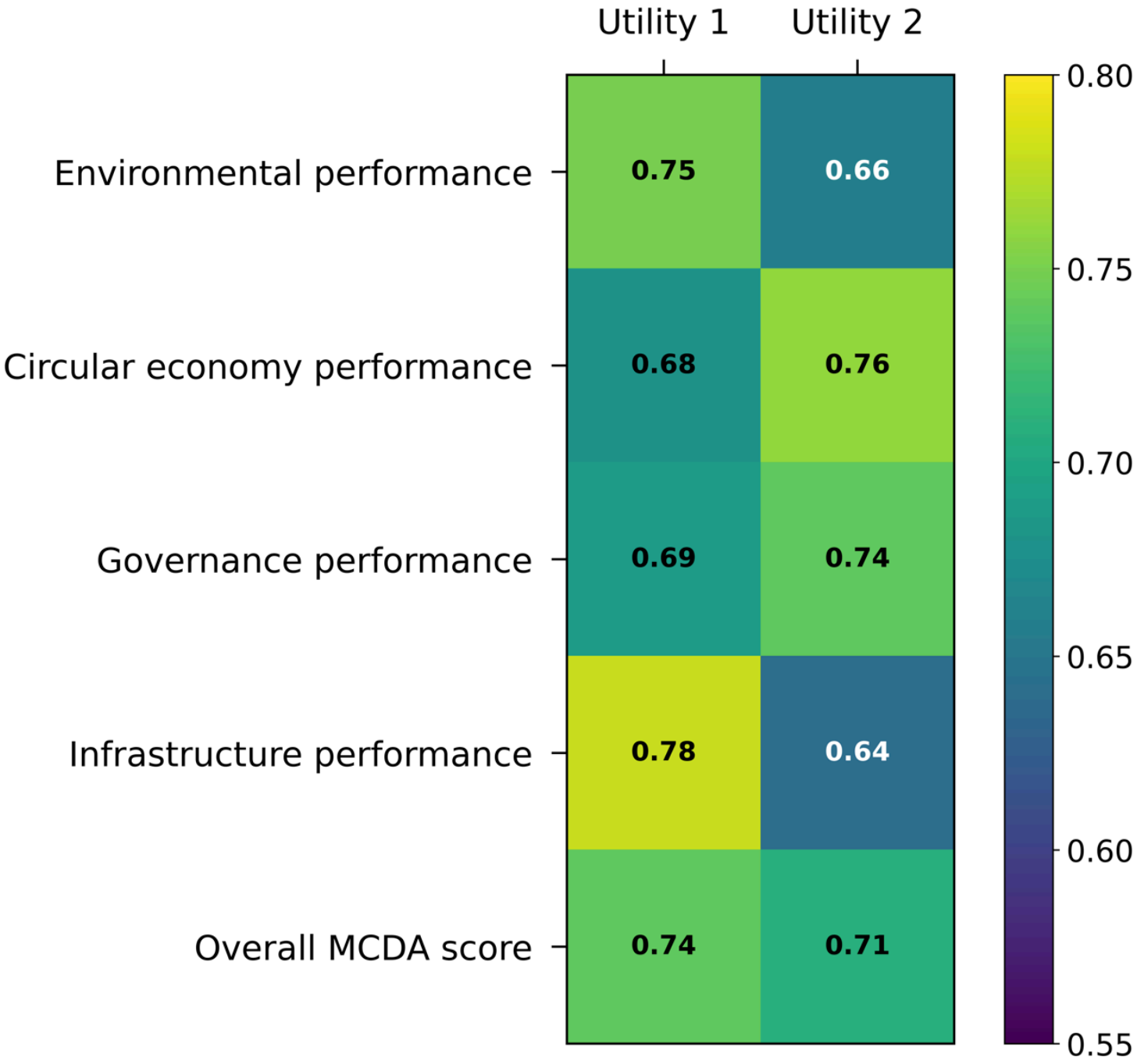


Figure 5

Integrated MCDA results and comparative heatmap analysis for two anonymized public water utilities. Prepared by the author.