Water Supply

Water Supply Vol 23 No 4, 1711 doi: 10.2166/ws.2023.076

Measuring the environmental performance of urban water systems: a systematic review

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ABSTRACT

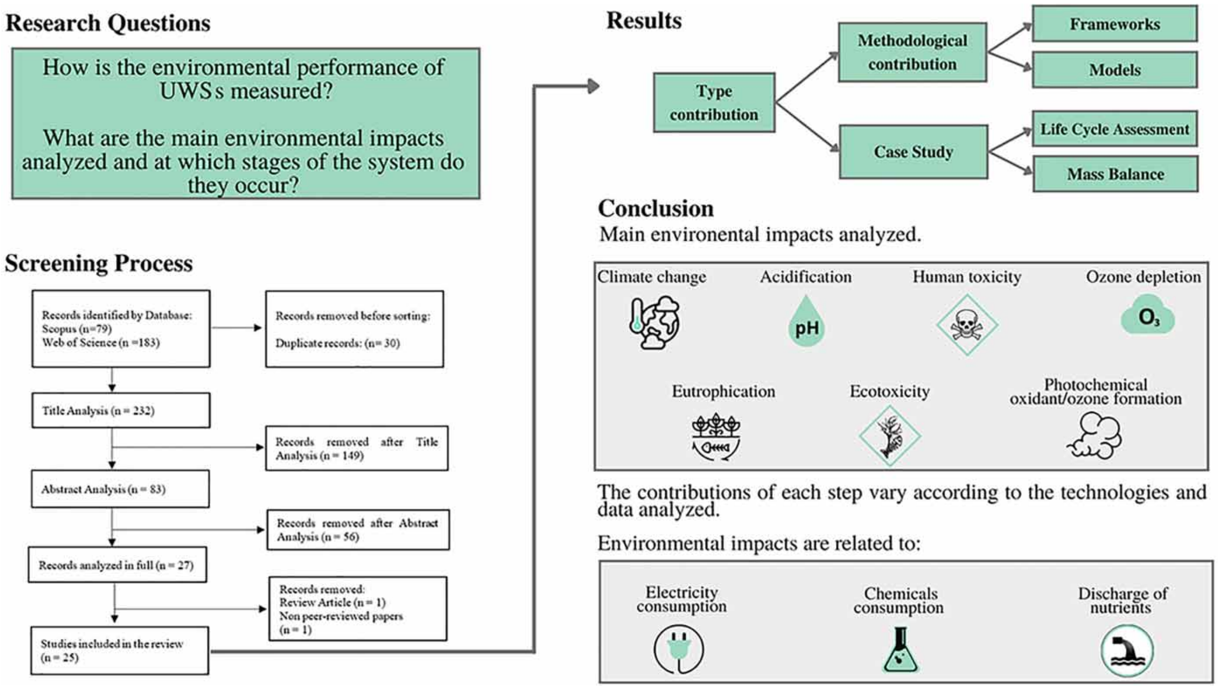
This systematic review aims to understand how previous studies have determined the environmental performance of urban water systems (UWSs) and to identify the main environmental impacts caused by these systems and their respective sources. A systematic review strategy based on the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) guidelines was used. The publications were selected by searching the *Scopus* and *Web of Science* databases last updated on 8 February 2022 and according to the eligibility criteria that were set for the present study. A total of 25 publications were analyzed in their entirety. Six publications presented methodological contributions by proposing frameworks and models for the analysis of environmental and sustainability parameters of urban water and sewage systems. Nineteen publications conducted case studies where life cycle assessment (LCA) and mass balance methods were employed. The categories of environmental impacts most frequently analyzed in the publications included climate change, eutrophication, acidification, and human toxicity. Moreover, the sources of these negative impacts were identified as high electricity consumption, chemical use, and nutrient discharge into the environment. The present review analyzes the contributions to each stage of the systems that are associated with the characteristics of the systems and the level of detail of the used data.

Key words: climate changes, environmental impacts, life cycle assessment, mass balance, ReCiPe method

HIGHLIGHTS

- Studies (methodologies and cases) on urban water system performance were reviewed.
- The life cycle assessment was identified as a commonly used tool for analysis.
- Impact on climate change was analyzed in all reviewed studies.
- Electricity consumption is an important source of environmental impacts.
- Contributions of each step vary according to the technologies and data analyzed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

In recent decades, environmental issues have been more comprehensively discussed to identify actions and strategies for the monitoring and reduction of environmental impacts from anthropological activities. Moreover, governments, researchers, entrepreneurs, and consumers participate in these discussions. Water supply and sanitary sewage services are essential for economic activities, the preservation of the environment, and the well-being and health of the public. However, utility companies continue to face challenges that complicate the sustainability of their operations, such as extreme weather events, ageing infrastructure, population growth, increasing coverage, and the need for improved quality (Alegre *et al.* 2006; EPA 2018; Xue *et al.* 2019).

Performance evaluations can be used to address some of these challenges. A system of indicators can be adopted to measure the quality, efficiency, and effectiveness of management operations; this can serve as a tool for planning and expanding services (Alegre *et al.* 2006; Vilanova *et al.* 2015).

In addition to measuring operational indicators, urban water systems (UWSs) can be evaluated using multiple environmental and sustainability parameters, thus allowing for the provision of water and sanitation services that can promote the environmental, economic, and social health of communities (Behzadian & Kapelan 2015a; Xue *et al.* 2019; Landa-Cansigno *et al.* 2020). The growing stakeholder interest in environmental performance has caused numerous organizations to establish procedures for monitoring and measuring the potential environmental impact of their activities, as guided by environmental management systems (ISO 2015; Galant & Cvek 2021).

Indicators are used in environmental performance assessment to determine the performance of an organization based on its environmental benchmarks over different time periods (ISO 2013). Recent studies show that investments in environmental performance contribute to improved financial performance (Lee *et al.* 2014; Galant & Cvek 2021) and increased organizational performance (Huynh 2020) and positively affect the competitiveness of companies (Martínez & Poveda 2022). Moreover, the identification and quantification of environmental impacts related to UWSs provide significant information to the formulators of management instruments and public policies related to the sector (Loubet *et al.* 2014).

The environmental performance of UWSs has been reviewed in the past; however, these studies selected more specific subjects, such as those related to the water sector in South Africa (Buckley *et al.* 2011), the environmental burden of wastewater treatment systems (Corominas *et al.* 2013), or the environmental impact of sewage treatment plant sludge (Yoshida *et al.*

2013). Some reviews have also considered all stages associated with the water system; however, they reviewed the application of a specific environmental impact quantification methodology, life cycle assessment (LCA) (Loubet *et al.* 2014; Byrne *et al.* 2017). No review has identified and analyzed publications related to measuring the environmental performance of UWS broadly.

Therefore, this systematic review aimed to elucidate the different methods of measuring the environmental performance of UWSs and to identify the main environmental impacts of UWS operations and their respective sources. In this review, UWSs refer to an integrated set of stages comprising water collection, water treatment, water distribution, sewage collection, and sewage treatment.

2. METHOD

2.1. Search strategy

A comprehensive literature review was conducted based on the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) guidelines. This method contributes toward transparent communication regarding the motivations for conducting a systematic review, the process by which it was performed and the results (Page *et al.* 2021). The PRISMA checklist is given in the Supplementary Material. The *Scopus* and *Web of Science* databases were selected as the sources of the articles. *Scopus* was selected for its broad coverage of management and engineering journals (Ahi & Searcy 2013), and *Web of Science* was selected for its focus on management (Shepherd & Günter 2006).

Our research questions were as follows:

(1) How is the environmental performance of UWSs measured?
(2) What are the main environmental impacts analyzed and at which stages of the system do they occur?

The terms used in the database searches were based on the questions above and are presented in Table 1.

2.2. Eligibility criteria and screening process

Articles were screened based on the eligibility criteria developed for this study as presented in Table 2.

The set of eligible studies was selected based on title, abstract, and full text screening processes. The initial database search yielded 262 records, and after removing duplicates, 232 records remained. The title screening excluded 149 records and

Table 1 | Search terms used per database

Scopus	***Web of Science***
'environmental impact' OR 'environmental performance' OR 'environmental sustainability'	'environmental impact' OR 'environmental performance' OR 'environmental sustainability'
AND	AND
'urban water system' OR 'integrated water system' OR 'integrated water supply and wastewater system' OR 'UWS'	'urban water system' OR 'integrated water system' OR 'integrated water supply and wastewater system' OR 'UWS'

Table 2 | Inclusion criteria for reviewing the studies

Criteria	**Inclusion**	**Exclusion**
Type of literature	Peer-reviewed papers	Conference proceedings, review articles, and editorial material
Place of study	Integrated water supply and wastewater systems	Industries, isolated components of water supply, and wastewater systems
Focus of investigation	Methodological and practical contributions to environmental performance measurement, environmental impact identification and assessment, systems stage analysis, and potential impact assessment methods	Papers that exclusively measure operational or financial performance of systems or that measure environmental performance of system infrastructure (excluding the operation)
Language	English	Other language

retained 83 records. Thereafter, the abstracts of the 83 records were screened and 27 articles were selected for full analysis; however, two records were excluded for not meeting the eligibility criteria. The process of identification, screening, eligibility, and inclusion of articles is shown in Figure 1 and was carried out by a single researcher. The results were analyzed by a second researcher and discrepancies were resolved through meetings between them.

2.3. Data extraction

Information related to the general data (year of publication, journal, and country of origin) and specific characteristics (methodological/practical contribution, methods used, impacts analyzed, and characteristics of the systems studied) were extracted for each publication. The record of the extracted data, as well as their organization, summarization, and creation of graphics, was performed in Microsoft Excel 365.

3. RESULTS AND DISCUSSION

3.1. Bibliographic review

Figure 2 summarizes the distribution of publication time, contribution type, and the journals containing the analyzed publications. The time distribution of the studies ranged from 2000 to 2022. Between 2000 and 2009, the number of publications related to UWSs was low (approximately one publication per year). The number of publications increased from 2010 and the highest number of publications was reported during 2015–2016 (five and four publications, respectively).

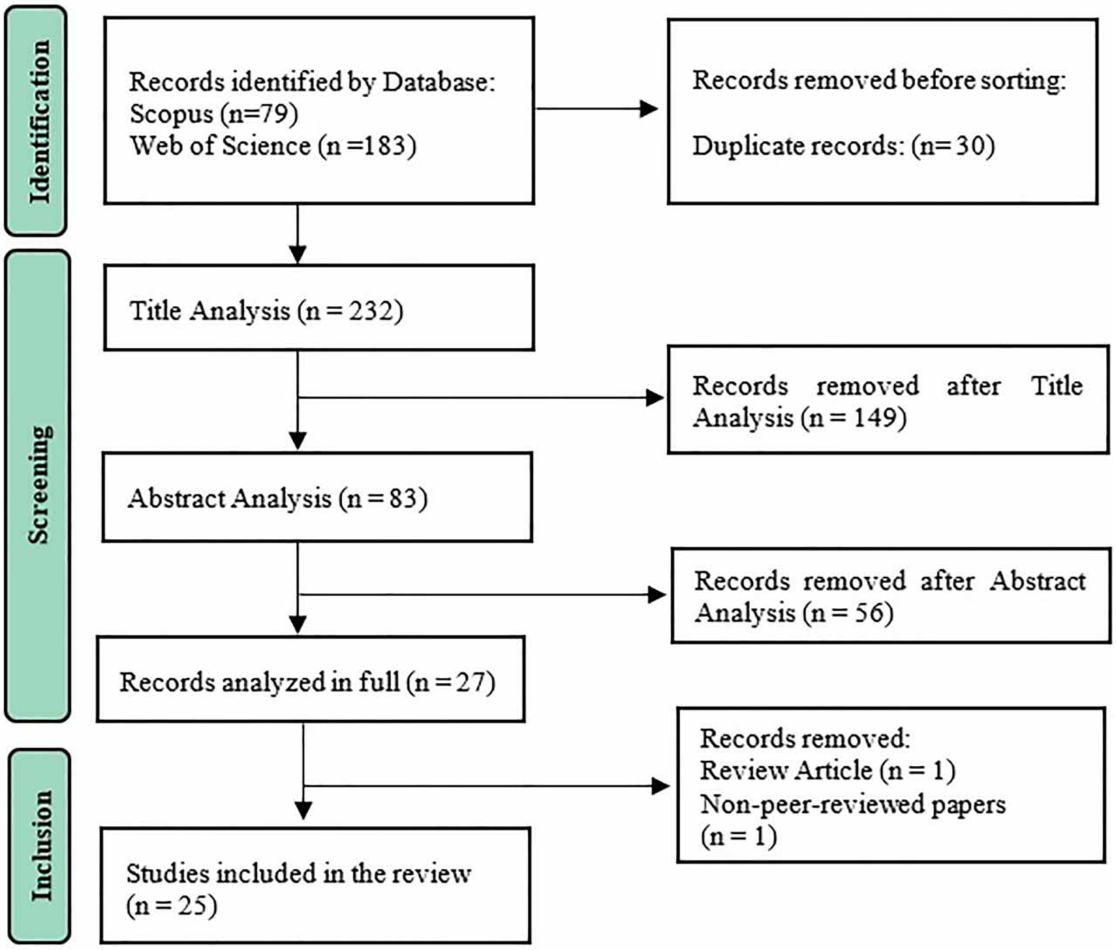


Figure 1 | Process of selecting publications.

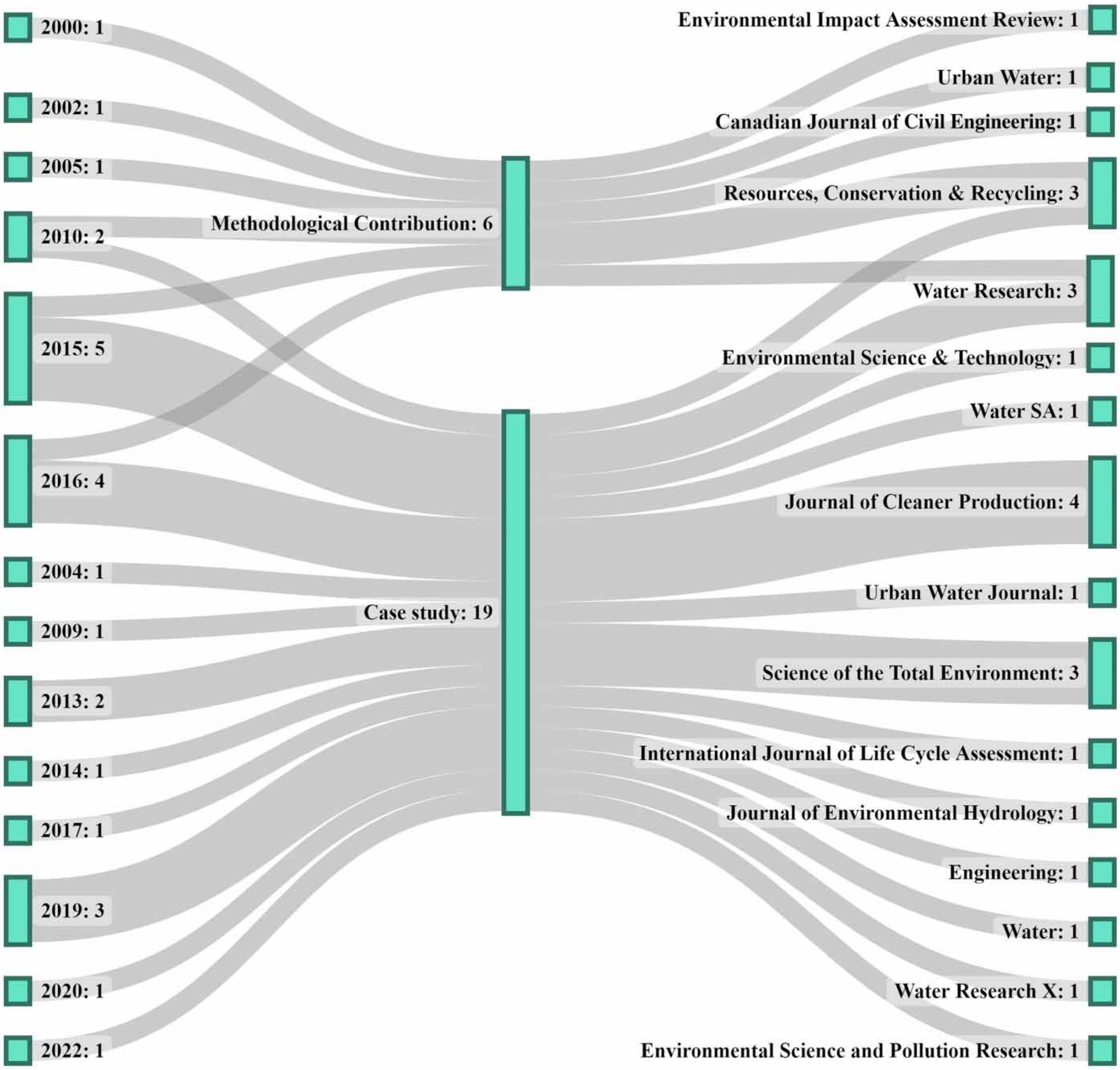


Figure 2 | Year of publication, type of contribution, and journals.

The initial studies related to the measurement of the environmental performance of UWSs included methodological contributions, where frameworks and models were presented and environmental performance indicators were suggested. From 2010 onwards, the publication of case studies that quantified the environmental impacts of these systems began.

The *Journal of Cleaner Production* had the highest number of publications in this field with four publications, followed by *Water Research*, *Science of the Total Environment*, and *Resources, Conservation and Recycling* with three publications each. However, the *Journal of Cleaner Production* and *Science of the Total Environment* published only case studies, whereas *Resources*, *Conservation and Recycling* and *Water Research* published both studies with methodological contributions as well as case studies. The number of publications in the other journals was lower and comprised a single study each.

Analysis of the geographical distribution of publications (Figure 3) showed that countries with the highest number of published studies were Australia (three publications, 12% of total publications), the United States of America, France, Mexico, and the Northern European region (two publications, 8% of total publications).

Among the continents, Europe had the largest number of publications (11 publications), followed by North America, Latin America, Asia, and Oceania with three publications each and Africa with two publications. Developed countries made the

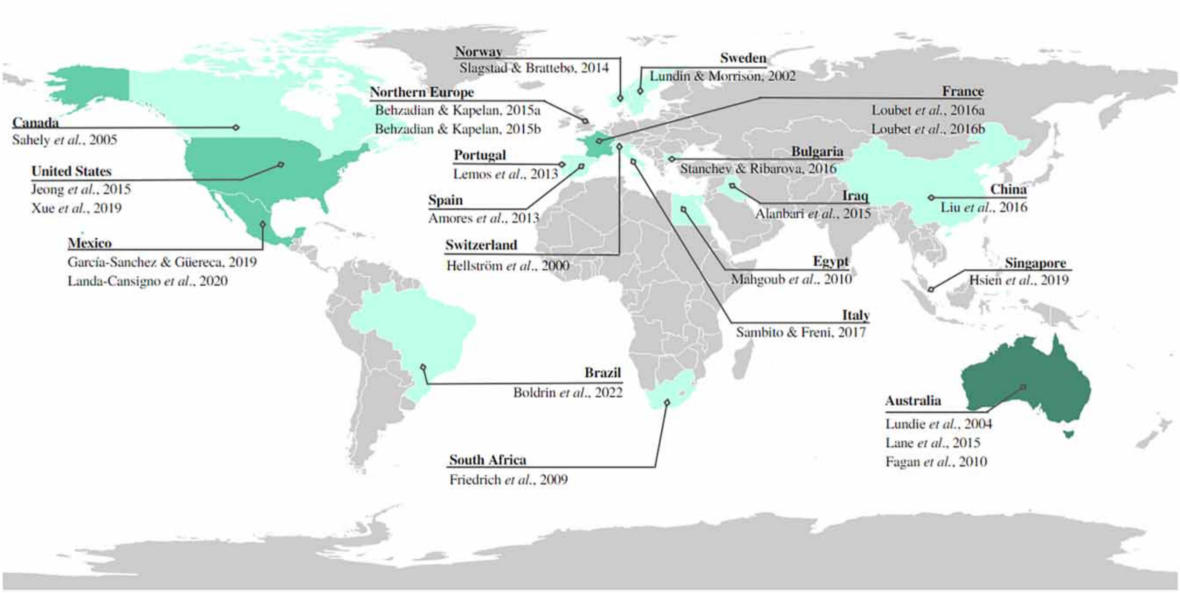


Figure 3 | Geographical distribution of studies.

greatest contribution to the total number of publications (17 publications), while underdeveloped or developing countries contributed eight publications in total.

Table 3 summarizes the 25 publications that were reviewed, along with a brief description of their objectives and main results. In this review, the studies were classified as 'studies with methodological contributions' or 'case studies based on the type of contribution'.

3.2. Methodological contributions

Hellström *et al.* (2000) proposed the first specific framework for measuring the environmental performance of UWSs to analyze and compare their sustainability criteria. This study is based on the separation of the water system into modular blocks that can be combined in different ways, making it possible to obtain different types of water management systems. The study analyzed multidimensional criteria involving economic, environmental, social, cultural, technical, and health aspects. For each of these aspects, the study identified quantifiable indicators that allow for analysis and comparison between the systems (Hellström *et al.* 2000).

Subsequent studies aimed to assess the UWS using the LCA framework. These frameworks were proposed for the evaluation of the environmental sustainability of UWSs (Lundin & Morrison 2002) or, in a broader sense, of any urban infrastructure (Sahely *et al.* 2005). According to these analyses, the most relevant environmental sustainability indicators for UWSs included electricity consumption, chemicals, greenhouse gas (GHG) emissions from wastewater treatment, nutrient discharge, sludge disposal, and nutrient and energy recycling. In addition, other studies proposed specific models for the simulation and analysis of UWSs. These models were based on the modeling of dynamic systems (Fagan *et al.* 2010), mass and energy balances (Behzadian & Kapelan 2015b), and object-oriented programming (Loubet *et al.* 2016b) to provide performance metrics, aid in the analysis of UWSs, or reduce their complexity.

The framework for modeling dynamic systems proposed by Fagan *et al.* (2010) was developed and linked to an LCA tool. This can provide a set of metrics that integrate all subsystems of the water cycle. The dynamic balance between the materials and energy, thermodynamics, and kinetics associated with an LCA and the economy of the process enables the analyzed variables to be calculated simultaneously throughout the analyzed system. The model was tested using a case study that compared the use of the framework at three scales of infrastructure. Its dynamic nature allows the water system to be designed for extreme events and assists in searching for alternatives that reduce its environmental impacts. The model's application also determined that the GHG emissions from the operation of the UWS were equal to or greater than those of the infrastructure; therefore, actions to improve the environmental performance of the UWS must first focus on the operation phase.

Table 3 | List of analyzed publications along with their objectives and main results

Source	Objective of the article	Type of contribution	Main results
Hellström *et al.* (2000)	Presents a framework for sustainability analysis of UWSs.	M	The framework separates the water system into modular blocks that can be combined in different ways, thereby making it possible to obtain a wide range of water management systems. They define a set of sustainability criteria to be considered when evaluating UWSs.
Lundin & Morrison (2002)	Presents an iterative procedure for selecting Environmental Sustainability Indicators using an outcome-based framework and LCA methodology.	M	The proposed iterative procedure is based on the LCA framework, and its application enabled the identification of relevant environmental sustainability indicators for the UWS.
Lundie *et al.* (2004)	Examines the potential environmental impacts of Sydney's (Australia) UWS.	S	Energy and chemical consumption contribute considerably to the environmental impacts analyzed. The construction of the infrastructure contributes little to environmental impacts compared with the operation of the system.
Sahely *et al.* (2005)	Develops a framework for sustainability assessment of urban infrastructure systems.	M	A set of sustainability criteria and sub-criteria are presented. The following are proposed as environmental sustainability indicators: electricity consumption, chemicals, GHG emissions from wastewater treatment, and treated effluent discharges.
Friedrich *et al.* (2009)	Generate information on the life cycle environmental profile of water in an urban context in eThekwini Municipality (South Africa).	S	Power consumption and water losses in the supply system are the major contributors to the environmental burden of these systems.
Mahgoub *et al.* (2010)	Develops scenarios to improve the total environmental performance and sustainability of the Alexandria UWS.	S	The biggest environmental impacts are related to the sewage treatment plants due to the low efficiency in nutrient removal. Electricity consumption contributes significantly to the impact of the analyzed categories.
Fagan *et al.* (2010)	Presents a dynamic system modeling framework aimed at providing a comprehensive set of performance metrics integrating all water cycle subsystems.	M	The model characteristics allow for the design of the water system for extreme events and for consideration of different possibilities to reduce the environmental impacts of its infrastructure and its embodied energy. Owing to its generality, the model is transferable to other water systems.
Amores *et al.* (2013)	Assesses the environmental profile of the urban water cycle in a Mediterranean city.	S	The water distribution contributed significantly to the environmental impacts of the urban system due to the orography of the site that requires a large number of water pumping stations, thus increasing the consumption of electrical energy. The use of chemicals contributed significantly to the impact categories of ozone depletion and cumulative energy demand.
Lemos *et al.* (2013)	Assesses and analyzes the environmental impacts associated with the UWS in the municipality of Aveiro (Portugal) using the LCA.	S	The effluent treatment and final disposal stage made the highest contribution to the impact categories of marine eutrophication and marine ecotoxicity owing to the concentrations of nitrogen and phosphorus in the effluent discharged into the sea. In the other stages of the system, the main contribution to environmental impacts was related to electrical energy consumption.

(*Continued.*)

Table 3 | Continued

Source	Objective of the article	Type of contribution	Main results
Slagstad & Brattebø (2014)	Quantifies the potential life cycle environmental impacts of the water and the wastewater system in Trondheim (Norway).	S	Electricity and chemical consumption contributed significantly to the environmental impacts of the analyzed system. The infrastructure also contributed significantly to the potential impacts.
Behzadian & Kapelan (2015b)	Expands the concept of metabolism-based modeling to derive a conceptual simulation model based on the specific representation of an UWS.	M	The model proved to be effective in assessing the sustainability of UWSs and the suitability of its use in strategic planning of the UWS.
Behzadian & Kapelan (2015a)	Explores the impact of the integration of UWS components on metabolism-based performance assessment when different strategies are applied.	S	While the integrated UWS prefers strategies that support the water supply and stormwater/residual water subsystems, the water supply systems favor strategies that aim at improving water-supply-related components only.
Jeong *et al.* (2015)	Performs an LCA for the centralized water system of Atlanta (USA).	S	The construction of the infrastructure of the analyzed system, the electricity consumption, and the water pollutants in stormwater runoff made the greatest contribution to the environmental impacts analyzed.
Alanbari *et al.* (2015)	Assesses the sustainability of the UWS of Al-Hilla (Iraq).	S	The sewage collection network and sewage treatment plants contributed most to the impact of the categories analyzed. Cement, steel, and electricity from fossil fuels made the greatest contribution to environmental impacts.
Lane *et al.* (2015)	Assesses the life cycle of two urban-scale water systems to analyze their potential environmental impacts.	S	Electricity use is an important driver of indirect environmental impacts throughout the life cycle of UWSs. The more diverse water supply mix considered in this study substantially increases system energy consumption.
Loubet *et al.* (2016b)	Models the complex UWSs of large cities within the LCA framework to assess their environmental impacts.	M	Owing to the proposed modular framework, various scenarios of UWSs can be tested by applying the model. The model can be improved by providing standard data, more optimized water quality management, and implementing uncertainty analysis.
Loubet *et al.* (2016a)	Implements the WaLa model in a real case study to evaluate the environmental impacts and services provided by UWSs in different scenarios.	S	Sewage treatment technologies have contributed significantly to environmental impacts owing to their consumption of electricity and chemicals. The adoption of emerging technologies for sewage treatment to recover energy and recycle nutrients can reduce the environmental impacts of this stage of the system.
Stanchev & Ribarova (2016)	Evaluates the eco-efficiency of a UWS based on the requirements of the ISO 14045 standard (Eco-efficiency).	S	They divide the analyzed system into foreground and background. The impact related to the foreground system is perceived only in the water intake and by the pollution load of the sewage system (measured as eutrophication). The impact of the background system is attributed to the three main inputs: energy, chemicals, and transportation, which fall into several impact categories and correspond to the largest negative environmental impact of the system.

Liu *et al.* (2016)	To evaluate the environmental performance of an urban-scale water system incorporating the use of seawater and reclaimed water for toilet flushing and compare its environmental impacts with a conventional system.	S	The seawater desalination process presented the most significant environmental impacts. The other scenarios presented impacts that were similar to each other. The results support the environmental sustainability of using seawater for toilet flushing, but its potential application depends on the proximity to the sea and the effective city population density.
Sambito & Freni (2017)	To quantify the carbon footprint of an integrated UWS using the LCA methodology.	S	The water collection and treatment stages present the greatest contributions to the impact category analyzed mainly due to the high consumption of electricity in pumping stations and water treatment plants. The sewage treatment plant also makes a significant contribution.
(Hsien *et al.* (2019))	To study the environmental impacts of Singapore's public water supply system using an LCA (considering water recycling and traditional treatment system).	S	The desalination process had the highest environmental impact in several categories mainly owing to the consumption of electricity and the impact embedded in the membrane used in the reverse osmosis treatment. The use of chemicals, materials, transport, and waste also contribute significantly to environmental impacts.
García-Sánchez & Güereca (2019)	Evaluates and analyzes the environmental and social performance of Mexico City's water system through an LCA.	S	Water distribution made the greatest contribution to environmental impacts owing to the high energy consumption in the pumping processes. They analyzed the impacts prevented by the operation of the sewage treatment plant through the removal of nutrients; therefore, this stage presented positive environmental impacts in this study.
Xue *et al.* (2019)	Presents an environmental and economic life cycle analysis of a UWS in the Greater Cincinnati region (USA).	S	The infrastructure stage presented insignificant environmental impacts compared with the system operation impacts. Power consumption and wastewater discharge from the sewage treatment plant contribute significantly to the environmental impacts analysed.
Landa-Cansigno *et al.* (2020)	Explores the impact assessment of water reuse strategies in UWSs using the integrated urban water metabolism assessment framework and the water–energy–pollution nexus.	S	The contribution of all system stages to the GHG emission category are directly related to the consumption of electricity and fossil fuels and indirectly to the consumption of chemicals. The sewage treatment plant is the largest contributor to the eutrophication impact category through nutrient discharge.
Boldrin *et al.* (2022)	To evaluate the environmental performance of an integrated water supply and wastewater treatment system that employs a lagooning system for wastewater treatment.	S	The water collection and wastewater treatment stages are the most significant contributors to the environmental impacts of the analyzed system. These impacts are caused mainly by the consumption of electricity, chemicals, and the emission of gases in the sewage treatment plant.

M, methodological contribution; S, case study.

Behzadian & Kapelan (2015b) proposed a conceptual model based on mass balance called WaterMet2. This is a dynamic model of mass flow analysis that allows the simulation of the flows related to the UWS with daily intervals and an analysis of the environmental impacts over a long-term duration. This model proved to be useful to measure the performance of the UWS considering different system configurations in the long term. Its application demonstrated that wastewater treatment plants were identified as the main sources of GHG emissions and acidification potential; but the source of eutrophication was shared between the wastewater treatment plant and the wastewater collection network.

The WaLA model proposed by Loubet *et al.* (2016b) used generic components to represent the UWS units, their users, and associated water flows and impacts. The model allowed the construction of analysis scenarios that connected technologies and users in a modular and integrated manner, and this enabled the model to calculate the impacts of the life cycle of the analyzed system. The model was tested through a virtual case study and demonstrated that systems can easily be built using the modular approach. The results indicated a significant contribution of wastewater treatment plants to local environmental impacts, such as eutrophication; but supporting activities, such as electricity, chemicals, and infrastructure, contributed toward global environmental impacts.

3.3. Case studies

Table 4 classifies the case studies according to the methods used and the characteristics of their application.

The studies aimed to analyze and identify the environmental impacts of UWS (Friedrich *et al.* 2009; Amores *et al.* 2013; Lemos *et al.* 2013; Slagstad & Brattebø 2014; Alanbari *et al.* 2015; Jeong *et al.* 2015; Loubet *et al.* 2016a; Sambito & Freni 2017; Boldrin *et al.* 2022). In addition, certain studies assessed the environmental impacts to improve the environmental performance (Mahgoub *et al.* 2010) by comparing two urban-scale water systems (Lane *et al.* 2015) and analyzing the environmental impacts of novel strategies and technologies (Liu *et al.* 2016; Hsien *et al.* 2019; Landa-Cansigno *et al.* 2020).

Certain studies have complemented the assessment of the environmental impacts of UWSs by including assessments of the social (García-Sánchez & Güereca 2019) and economic (Behzadian & Kapelan 2015a; Stanchev & Ribarova 2016; Xue *et al.* 2019) dimensions; these studies provide a more comprehensive analysis of UWS performance.

3.3.1. Evaluation methods and system boundary

The quantification of the environmental impacts of UWSs was conducted using the LCA and mass balance methodologies.

Some publications applied the WaterMet2 model to analyze UWSs (Behzadian & Kapelan 2015a; Landa-Cansigno *et al.* 2020). Issues related to the strategic planning of UWSs were analyzed by Behzadian & Kapelan (2015a); they found that conventional and sustainability indicators are necessary for the strategic planning of UWSs. In addition, Landa-Cansigno *et al.* (2020) considered a range of centralized and decentralized water reuse strategies. They identified that decentralized water reuse strategies yield more optimized performance with respect to water conservation, GHG emissions, and eutrophication indicators, while energy savings are negligible. They also concluded that centralized strategies could achieve more optimized energy-saving performance.

The LCA can assess material input and output flows throughout the life cycle of a given product and estimate its potential environmental impacts (ISO 2006). It offers a holistic approach for the evaluation of UWSs and its analysis should include the construction, operation, and decommissioning stages of the facilities (Loubet *et al.* 2014). However, this is not always possible due to the lack of actual data. In addition, the use of databases is limited, as in some cases, researchers use data from other regions.

Regarding the operational process of UWSs, the water withdrawal, water treatment, water distribution, sewage collection, and sewage treatment stages were considered in all case studies except that performed by Friedrich *et al.* (2009), which did not include the water withdrawal stage.

Some system stages, such as water use by consumers (Lundie *et al.* 2004; Loubet *et al.* 2016a; García-Sánchez & Güereca 2019), rainwater (Jeong *et al.* 2015; Loubet *et al.* 2016a; Xue *et al.* 2019), and water recycling processes (Friedrich *et al.* 2009; Hsien *et al.* 2019), were relatively rare in case studies. Moreover, the environmental impacts related to UWS infrastructure were not included in all studies. However, infrastructure can be considered in its entirety (Lundie *et al.* 2004; Friedrich *et al.* 2009; Jeong *et al.* 2015; Lane *et al.* 2015; Loubet *et al.* 2016a; Xue *et al.* 2019) or partially (Amores *et al.* 2013; Lemos *et al.* 2013; Slagstad & Brattebø 2014; Alanbari *et al.* 2015; Boldrin *et al.* 2022).

The analysis of UWSs using the LCA must include a volume metric as a functional unit (Loubet *et al.* 2014; Byrne *et al.* 2017). In the analyzed publications, the functional units varied among the supply or distribution of 1 m^3 of drinking water (53% of all publications), the supply of 1 m^3 of drinking water or the treatment of 1 m^3 of sewage (16% of the publications),

Table 4 | Main characteristics of the case studies reviewed

			Analyzed system stages									
Source	**Method**	**LCIA method**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**Functional unit**
Lundie *et al.* (2004)	LCA	Not informed	x	x	x	x	x	x			x	Provision of water supply and sewage services in 2021
Friedrich *et al.* (2009)	LCA	CML		x	x		x	x		x	x	Supply of 1 m^3 of drinking water
Mahgoub *et al.* (2010)	LCA	Eco-Indicator 99	x	x	x		x	x				1 m^3 of drinking water or 1 m^3 of treated sewage
Amores *et al.* (2013)	LCA	CML, Freshwater Use, Cumulative Energy Demand, FEI	x	x	x		x	x			x	Supply of 1 m^3 of drinking water
Lemos *et al.* (2013)	LCA	ReCiPe	x	x	x		x	x			x	Supply of 1 m^3 of drinking water
Slagstad & Brattebø (2014)	LCA	ReCiPe	x	x	x		x	x			x	One year of water supply and wastewater collection, transport, and treatment
Behzadian & Kapelan (2015a)	Mass balance	Not informed	x	x	x		x	x				Not informed
Jeong *et al.* (2015)	LCA	TRACI, FEI	x	x	x		x	x	x		x	Distribution of 1 m^3 of water
Alanbari *et al.* (2015)	LCA	IMPACT2002 +	x	x	x		x	x			x	1 m^3 of drinking water or 1 m^3 of treated sewage
Lane *et al.* (2015)	LCA	ReCiPe, CML, USES LCA 2.0, WSI	x	x	x		x	x			x	One year of water supply and wastewater collection, transport, and treatment
Loubet *et al.* (2016a)	LCA	Water deprivation impact, IMPACT2002 +	x	x	x	x	x	x	x		x	Supply of 1 m^3 of drinking water
Stanchev & Ribarova (2016)	LCA	Not informed	x	x	x		x	x				Number of households served
Liu *et al.* (2016)	LCA	ReCiPe	x	x	x		x	x				Supply of 1 m^3 of drinking water
Sambito & Freni (2017)	LCA	Carbon footprint	x	x	x		x	x				Supply of 1 m^3 of drinking water
Hsien *et al.* (2019)	LCA	ReCiPe	x	x	x		x	x		x		Supply of 1 m^3 of drinking water
García-Sánchez & Güereca (2019)	LCA	ReCiPe	x	x	x	x	x	x				Supply of 1 m^3 of drinking water
Xue *et al.* (2019)	LCA	TRACI, ReCiPe, Cumulative Energy Demand, Water Footprint	x	x	x		x	x	x		x	Supply of 1 m^3 of drinking water
Landa-Cansigno *et al.* (2020)	Mass balance	CML, Cumulative Energy Demand	x	x	x		x	x				Not informed
Boldrin *et al.* (2022)	LCA	ReCiPe, Cumulative Energy Demand	x	x	x		x	x			x	1 m^3 of drinking water or 1 m^3 of treated sewage

A, collection; B, water treatment; C, water distribution; D, use; E, sewage collection; F, sewage treatment; G, rainwater collection; H, water recycling; I, infrastructure.

one year of water supply and collection, the transport and treatment of wastewater (16% of the publications), and the number of households served (5%). Two publications did not report the functional units (11% of the publications).

In addition, several publications were included in the scenario analysis considered in the present review, which aimed to elucidate the environmental impacts resulting from changes in system operation or infrastructure. The alternative scenarios were proposed considering mainly changes related to the reduction of water losses during distribution, seawater desalination processes, water recycling processes, adoption of new technologies for sewage treatment, changes in the mix of electric power used by the systems, and an increase in service demand and provision (Lundie *et al.* 2004; Mahgoub *et al.* 2010; Amores *et al.* 2013; Lemos *et al.* 2013; Lane *et al.* 2015; Liu *et al.* 2016; Loubet *et al.* 2016a; Hsien *et al.* 2019; Boldrin *et al.* 2022).

3.3.2. Evaluation of environmental impacts

Methods used in the life cycle impact assessment (LCIA) stage may consist of a single impact category analysis, such as cumulative energy demand, water footprint, carbon footprint, freshwater ecosystem impact (FEI), and water stress index (WSI). The cumulative energy demand, carbon footprint, and water footprint methods quantify the direct and indirect amounts of primary energy, carbon equivalent, and water that are used in certain activities, respectively (Jungbluth & Frischknecht 2007; Hoekstra *et al.* 2011). Water consumption is also evaluated using the FEI method, which assesses the ecological consequences of water use in a region, and the WSI method, which assesses the environmental impacts of freshwater consumption, and considers damage to human health, ecosystem quality, and resources (Milà i Canals *et al.* 2009; Pfister *et al.* 2009).

Other methods have multiple impact categories that can be selected according to the available input data and purpose of the analysis, such as ReCiPe, CML, Eco-indicator 99, Impact2002 + , TRACI, and the Uniform System for the Evaluation of Substances for LCA Purposes (USE LCA 2.0). The assessment of potential environmental impacts may consider an approach at the midpoint level, when the characterization of the environmental impact is performed along the environmental mechanism or endpoint, and when it is considered as an aspect of the natural environment, such as human health, ecosystems, and resources (ISO 2006).

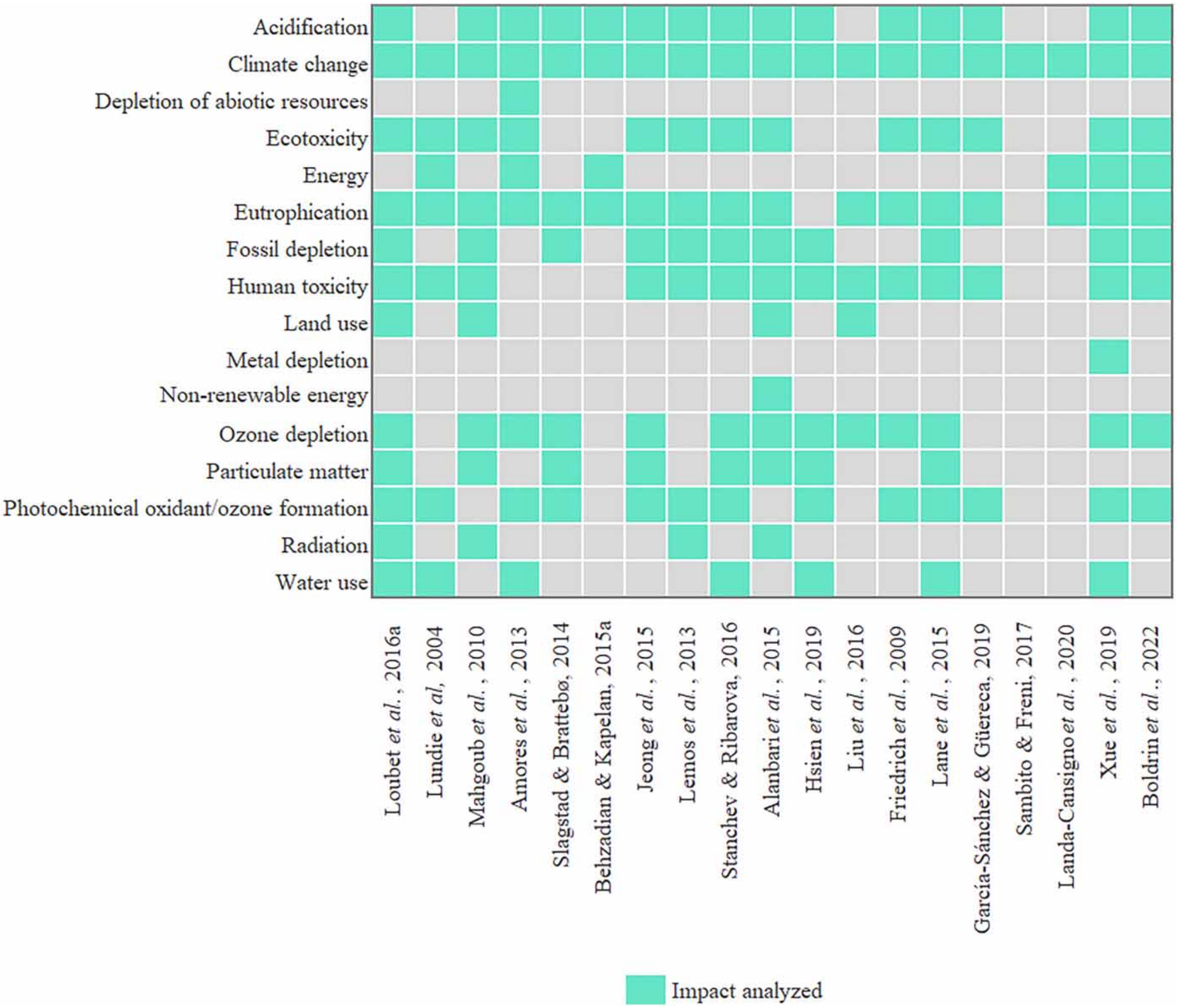
The CML and Eco-Indicator 99 methods were developed in the Netherlands, and while the CML presents a midpoint-level approach to assess environmental impacts, the Eco-Indicator 99 method sought to simplify the interpretation and weighting of LCA results through an approach endpoint (Guinée 2001; Joint Research Centre 2010; Mendes *et al.* 2006). The TRACI method consists of a method for assessing potential environmental impacts with a midpoint approach that considers the environmental conditions in the United States (Bare *et al.* 2003). The ReCiPe method was developed to integrate and harmonize the midpoint and endpoint approaches and consists of a continuation of the CML and Eco-Indicator 99 methods (Goedkoop *et al.* 2009; Joint Research Centre 2010). Methods such as Impact 2002+ and USES LCA 2.0 also integrate midpoint- and endpoint-level approaches into their impact categories. However, while Impact 2002+ allows for the analysis of 14 impact categories, the USES LCA 2.0 permits the quantification of environmental impacts related to ecotoxicity and human toxicity (Jolliet *et al.* 2003; van Zelm *et al.* 2009).

Some of the methods have similar impact categories; however, they may use different approaches and nomenclature. For example, the TRACI method proposed by Bare *et al.* (2003) and used by Jeong *et al.* (2015) introduced the eutrophication impact category. However, the ReCiPe method proposed by Goedkoop *et al.* (2009) subdivides the same impact category into marine eutrophication analyzed by Lemos *et al.* (2013) and freshwater eutrophication analyzed by Boldrin *et al.* (2022). Impact categories with different nomenclatures, but which express their results in the same unit, were also grouped. For example, 'climate change' and 'global warming' that present their results in kg CO_2-Eq. To simplify the presentation of results, Figure 4 summarizes the impact categories analyzed in the reviewed case studies. For example, regardless of whether the study analyzed marine or freshwater eutrophication, the information is summarized in Figure 4 as eutrophication. This applies to the other impact categories and a list of all nomenclatures is given in the Supplementary Material.

The only impact category analyzed in all publications is climate change, which is also referred to as global warming in some LCIAs. Analysis of eutrophication occured in 17 publications, while acidification and human toxicity were analyzed in 15 and 14 publications, respectively. Ozone depletion, photochemical oxidant/ozone formation, and ecotoxicity were analyzed in 13 publications. Fossil depletion and particulate matter were analyzed in 11 and eight publications, respectively. The other categories were analyzed less frequently as shown in the figure.

3.3.3. Main sources of environmental impacts

The most commonly identified sources of the environmental impacts of UWSs were electricity consumption, nutrient discharge into the environment, and chemicals used in the UWS.



	Loubet *et al.*, 2016a	Lundie *et al*, 2004	Mahgoub *et al.*, 2010	Amores *et al.*, 2013	Slagstad & Brattebø, 2014	Behzadian & Kapelan, 2015a	Jeong *et al.*, 2015	Lemos *et al.*, 2013	Stanchev & Ribarova, 2016	Alanbari *et al.*, 2015	Hsien *et al.*, 2019	Liu *et al.*, 2016	Friedrich *et al.*, 2009	Lane *et al.*, 2015	García-Sánchez & Güereca, 2019	Sambito & Freni, 2017	Landa-Cansigno *et al.*, 2020	Xue *et al.*, 2019	Boldrin *et al.*, 2022
Acidification	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩			🟩	🟩
Climate change	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Depletion of abiotic resources				🟩															
Ecotoxicity	🟩	🟩	🟩	🟩			🟩	🟩	🟩	🟩			🟩	🟩	🟩			🟩	🟩
Energy		🟩		🟩		🟩											🟩	🟩	🟩
Eutrophication	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩		🟩	🟩	🟩
Fossil depletion	🟩		🟩		🟩		🟩	🟩	🟩	🟩	🟩			🟩				🟩	🟩
Human toxicity	🟩	🟩	🟩				🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩			🟩	🟩
Land use	🟩		🟩							🟩		🟩							
Metal depletion																		🟩	
Non-renewable energy										🟩									
Ozone depletion	🟩		🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩	🟩	🟩				🟩	🟩
Particulate matter	🟩		🟩		🟩		🟩		🟩	🟩	🟩			🟩					
Photochemical oxidant/ozone formation	🟩	🟩		🟩	🟩		🟩	🟩	🟩		🟩		🟩	🟩	🟩			🟩	🟩
Radiation	🟩		🟩					🟩		🟩									
Water use	🟩	🟩		🟩					🟩		🟩			🟩				🟩	

🟩 Impact analyzed

Figure 4 | Impact categories analyzed in each publication.

The water collection and distribution stages, sewage collection and treatment, and seawater desalination process consume most of the required electricity (Friedrich *et al.* 2009; Mahgoub *et al.* 2010; Amores *et al.* 2013; Lemos *et al.* 2013; Alanbari *et al.* 2015; Lane *et al.* 2015; Loubet *et al.* 2016a; Stanchev & Ribarova 2016; Sambito & Freni 2017; Hsien *et al.* 2019; Xue *et al.* 2019; Boldrin *et al.* 2022). In addition, the use of water from underground springs or the pumping of water to cover the extensive distances between the points of collection and consumption increases the electricity consumption of the systems (Lundie *et al.* 2004; Amores *et al.* 2013; Alanbari *et al.* 2015; Jeong *et al.* 2015; Sambito & Freni 2017; García-Sánchez & Güereca 2019; Xue *et al.* 2019; Boldrin *et al.* 2022).

The environmental impacts arising from electricity consumption are a function of the energy mix used by each country or region. Therefore, the adoption of an energy matrix with higher participation of renewable energy can contribute considerably to reducing the environmental impacts of UWSs (Lemos *et al.* 2013; Sambito & Freni 2017; Boldrin *et al.* 2022). Furthermore, solutions such as the use of photovoltaic panels and energy recovery in wastewater treatment plants can also contribute to reducing these impacts (Friedrich *et al.* 2009; Boldrin *et al.* 2022). Another important factor that can help reduce energy consumption is the reduction of losses in distribution systems, as a considerable amount of energy is consumed to capture, treat, and distribute water that is not consumed (Lemos *et al.* 2013; Sambito & Freni 2017; Boldrin *et al.* 2022). According to Friedrich *et al.* (2009), the reduction of losses not only contributes to the advantages associated with the treatment and distribution of water but also prevents unnecessary wastage of water.

With respect to sewage treatment plants, the treated effluents are discharged into aquatic environments and excess nutrient discharge can result in the eutrophication of the aquatic environments (Lemos *et al.* 2013; Jeong *et al.* 2015). The application of treatment plant sludge to arable soils reduces the need for synthetic fertilizers, which leads to savings in energy, raw materials, and emissions from the production of these fertilizers. However, the application of sewage sludge increases the impact of potential eutrophication (Amores *et al.* 2013).

Unlike the other publications, García-Sanchez & Güereca (2019) reported that the sewage treatment plant presented the lowest system environmental impact owing to the low power consumption of the analyzed sewage treatment plant and the fact that the study used the Net Environmental Benefit (NEB) equation presented by Godin *et al.* (2012), which evaluates the impact avoided by the removal of pollutants in treated effluents. The study conducted by Boldrin *et al.* (2022) identified a significant contribution of the wastewater treatment plant in the impact categories of climate change and photochemical oxidant formation, resulting from methane emissions from the lagoon system used in the wastewater treatment plant.

Although electricity consumption and nutrient discharge contribute significantly to the environmental impacts of the analyzed systems, chemicals were notably responsible for significant environmental impacts (Stanchev & Ribarova 2016; Xue *et al.* 2019; Boldrin *et al.* 2022). Lundie *et al.* (2004) identified that chemicals contributed considerably to the total energy consumption indicators as well as to the categories of climate change and photochemical oxidant formation. Amores *et al.* (2013) found that chemicals contributed directly to the impact categories related to cumulative energy demand and stratospheric ozone destruction.

Regarding the infrastructure of UWSs, Lundie *et al.* (2004) concluded that the operational phase of the system is considerably more significant for environmental impacts than the infrastructure. However, subsequent studies have found that UWS infrastructure contributes significantly to the environmental impacts analyzed and therefore should be considered in the analyses whenever possible (Slagstad & Brattebø 2014; Jeong *et al.* 2015; Lane *et al.* 2015; Loubet *et al.* 2016a; Xue *et al.* 2019).

Significant variations related to the degree of contribution of each system step in environmental impacts may be associated with the characteristics of systems (the type of system or technology used) or the level of detail of input data used in the analysis. When actual data are unavailable, numerous researchers use simplifications or data from previous studies to compose the LCA inventory. Such simplifications limit the method, which may not correctly express the impacts related to the analyzed system.

Furthermore, studies related to measuring the environmental performance of UWSs are carried out individually to analyze a specific system and methodological variations in its application complicate comparative analysis between systems.

4. CONCLUSIONS

We conducted a systematic literature review to identify and analyze studies that measured the environmental performance of UWSs. Publications with two distinct contribution types such as methodological contributions and case studies were identified. The former included studies that contributed toward the development of frameworks and models, identifying relevant indicators to measure the environmental performance of UWSs. The case studies conducted an applied analysis of the environmental performance of the UWSs.

Our results identified models based on mass balance and LCA. However, the high usage of LCA in the analyzed publications suggests that it is the most accepted method for measuring the environmental performance of UWSs. The classification of the studies indicated that, within the application of LCAs, the most frequently used LCIA method was ReCiPe and the most frequently analyzed impact categories were climate change, eutrophication, acidification, human toxicity, photochemical oxidant/ozone formation, ecotoxicity, and fossil depletion.

The findings of the present review form the basis for future related studies that intend to develop new methodologies or tools to measure the environmental performance of the UWS. Moreover, they can aid in formulating plans and policies to improve the environmental performance of the UWS.

ACKNOWLEDGEMENTS

M.T.N.B. is thankful to the Coordination for the Improvement of Higher Education Personnel – Brazil (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – CAPES) for providing a doctoral scholarship grant.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ahi, P. & Searcy, C. 2013 A comparative literature analysis of definitions for green and sustainable supply chain management. *Journal of Cleaner Production* **52**, 329–341. doi:10.1016/j.jclepro.2013.02.018.

Alanbari, M. A., Alazzawi, H. Q., Al-Ansari, H. A. & Knutsson, S. 2015 Selecting sustainability indicators of urban water systems: case study of Al-Hilla City, Iraq. *Journal of Environmental Hydrology* **22**, 6.

Alegre, H., Baptista, J. M., Cabrera Jr, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W. & Parena, R. 2006 *Performance Indicators for Water Supply Services*. IWA Publishing, London, UK.

Amores, M. J., Meneses, M., Pasqualino, J., Antón, A. & Castells, F. 2013 Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of Cleaner Production* **43**, 84–92. doi:10.1016/j.jclepro.2012.12.033.

Bare, J. C., Norris, G. A. & Pennington, D. W. 2003 TRACI: The tool for the reduction and assessment of chemical and environmental impacts. *Journal of Industrial Ecology* **6** (3), 49–78. doi:10.1162/108819802766269539.

Behzadian, K. & Kapelan, Z. 2015a Advantages of integrated and sustainability based assessment for metabolism based strategic planning of urban water systems. *Science of the Total Environment* **527–528**, 220–231. doi:10.1016/j.scitotenv.2015.04.097.

Behzadian, K. & Kapelan, Z. 2015b Modelling metabolism based performance of an urban water system using WaterMet^2. *Resources, Conservation and Recycling* **99**, 84–99. doi:10.1016/j.resconrec.2015.03.015.

Boldrin, M. T. N., Formiga, K. T. M. & Pacca, S. A. 2022 Environmental performance of an integrated water supply and wastewater system through life cycle assessment – a Brazilian case study. *Science of the Total Environment* **835**, 155213. doi:10.1016/j.scitotenv.2022.155213.

Buckley, C., Friedrich, E. & von Blottnitz, H. 2011 Life-cycle assessments in the South African water sector: a review and future challenges. *Water SA* **37** (5), 719–726. doi:10.4314/wsa.v37i5.9.

Byrne, D. M., Lohmann, H. A. C., Cook, S. M., Peters, G. M. & Guest, J. S. 2017 Life cycle assessment (LCA) of urban water infrastructure: emerging approaches to balance objectives and inform comprehensive decision-making. *Environmental Science: Water Research & Technology* **3** (6), 1002–1014. doi:10.1039/c7ew00175d.

Corominas, L., Foley, J., Guest, J. S., Hospido, A., Larsen, H. F., Morera, S. & Shaw, A. 2013 Life cycle assessment applied to wastewater treatment: state of the art. *Water Research* **47** (15), 5480–5492. doi:10.1016/j.watres.2013.06.049.

EPA 2018 *Moving toward Sustainability: Sustainable and Effective Practices for Creating Your Water Utility Roadmap*. USEPA, Washington, DC, USA.

Fagan, J. E., Reuter, M. A. & Langford, K. J. 2010 Dynamic performance metrics to assess sustainability and cost effectiveness of integrated urban water systems. *Resources, Conservation and Recycling* **54** (10), 719–736. doi:10.1016/j.resconrec.2009.12.002.

Friedrich, E., Pillay, S. & Buckley, C. A. 2009 Environmental life cycle assessments for water treatment processes – a South African case study of an urban water cycle. *Water SA* **35** (1), 73–84. doi:10.4314/wsa.v35i1.76710.

Galant, A. & Cvek, D. 2021 The effect of environmental performance investments on financial performance: analysis of Croatian companies. *Central European Business Review* **10** (5), 37–51. doi:10.18267/j.cebr.271.

García-Sánchez, M. & Güereca, L. P. 2019 Environmental and social life cycle assessment of urban water systems: the case of Mexico City. *Science of the Total Environment* **693**, 133464. doi:10.1016/j.scitotenv.2019.07.270.

Godin, D., Bouchard, C. & Vanrolleghem, P. A. 2012 Net environmental benefit: introducing a new LCA approach on wastewater treatment systems. *Water Science and Technology* **65** (9), 1624–1631. doi:10.2166/wst.2012.056.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & van Zelm, R. 2009 *ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Report I: Characterisation*, 1st edn. Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands.

Guinée, J. 2001 Handbook on life cycle assessment – operational guide to the ISO standards. *International Journal of Life Cycle Assessment* **6** (5), 255.

Hellström, D., Jeppsson, U. & Kärrman, E. 2000 A framework for systems analysis of sustainable urban water management. *Environmental Impact Assessment Review* **20** (3), 311–321. doi:10.1016/S0195-9255(00)00043-3.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. 2011 *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, London, UK.

Hsien, C., Low, J. S. C., Fuchen, S. C. & Han, T. W. 2019 'Life cycle assessment of water supply in Singapore – a water-scarce urban city with multiple water sources. *Resources, Conservation and Recycling* **151**, 104476. doi:10.1016/j.resconrec.2019.104476.

Huynh, Q. L. 2020 Impacts of environmental responsibility and performance on organizational performance: importance of environmental performance. *International Journal of Energy Economics and Policy* **10** (6), 100–108. doi:10.32479/ijeep.9955.

ISO – International Organization for Standardization 2006 *ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework*. ISO, Geneva, Switzerland.

ISO – International Organization for Standardization 2013 *ISO 14031 Environmental Management – Environmental Performance Evaluation – Guidelines*. ISO, Geneva, Switzerland.

ISO – International Organization for Standardization 2015 *ISO 14001:2015 – Environmental Management Systems – Requirements with Guidance for Use*. ISO, Geneva, Switzerland.

Jeong, H., Minne, E. & Crittenden, J. C. 2015 Life cycle assessment of the City of Atlanta, Georgia's centralized water system. *International Journal of Life Cycle Assessment* **20** (6), 880–891. doi:10.1007/s11367-015-0874-y.

Joint Research Centre 2010 *International Reference Life Cycle Data System (ILCD) Handbook: Analysis of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment*. Publications Office of the European Union, Luxembourg.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G. & Rosenbaum, R. 2003 IMPACT 2002+: a new life cycle impact assessment methodology. *International Journal of Life Cycle Assessment* **8** (6), 324–330. doi:10.1007/BF02978505.

Jungbluth, N. & Frischknecht, R. 2007 Cumulative energy demand. In: *Implementation of Life Cycle Impact Assessment Methods* (Frischknecht, R. & Jungbluth, N., eds), Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland, pp. 31–38.

Landa-Cansigno, O., Behzadian, K., Davilo-Cano, D. I. & Campos, L. C. 2020 Performance assessment of water reuse strategies using integrated framework of urban water metabolism and water-energy-pollution nexus. *Environmental Science and Pollution Research* **27** (5), 4582–4597. doi:10.1007/s11356-019-05465-8.

Lane, J. L., de Haas, D. W. & Lant, P. A. 2015 The diverse environmental burden of city-scale urban water systems. *Water Research* **81**, 398–415. doi:10.1016/j.watres.2015.03.005.

Lee, K. H., Cin, B. C. & Lee, E. Y. 2014 Environmental responsibility and firm performance: the application of an environmental, social and governance model. *Business Strategy and the Environment* **25** (1), 40–53. doi:10.1002/bse.1855.

Lemos, D., Dias, A. C., Gabarrell, X. & Arroja, L. 2013 Environmental assessment of an urban water system. *Journal of Cleaner Production* **54**, 157–165. doi:10.1016/j.jclepro.2013.04.029.

Liu, X., Dai, J., Wu, D., Jiang, F., Chen, G., Chui, H. K. & van Loosdrecht, M. C. M. 2016 Sustainable application of a novel water cycle using seawater for toilet flushing. *Engineering* **2** (4), 460–469. doi:10.1016/J.ENG.2016.04.013.

Loubet, P., Roux, P., Loiseau, E. & Bellon-Maurel, V. 2014 Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. *Water Research* **67**, 187–202. doi:10.1016/j.watres.2014.08.048.

Loubet, P., Roux, P., Guérin-Schneider, L. & Bellon-Maurel, V. 2016a Life cycle assessment of forecasting scenarios for urban water management: a first implementation of the WaLA model on Paris suburban area. *Water Research* **90**, 128–140. doi:10.1016/j.watres.2015.12.008.

Loubet, P., Roux, P. & Bellon-Maurel, V. 2016b WaLA, a versatile model for the life cycle assessment of urban water systems: formalism and framework for a modular approach. *Water Research* **88**, 69–82. doi:10.1016/j.watres.2015.09.034.

Lundie, S., Peters, G. M. & Beavis, P. C. 2004 Life cycle assessment for sustainable metropolitan water systems planning. *Environmental Science and Technology* **38** (13), 3465–3473. doi:10.1021/es034206m.

Lundin, M. & Morrison, G. M. 2002 A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. *Urban Water* **4** (2), 145–152. doi:10.1016/S1462-0758(02)00015-8.

Mahgoub, M. E.-S. M., van der Steen, N. P., Abu-Zeid, K. & Vairavamoorthy, K. 2010 Towards sustainability in urban water: a life cycle analysis of the urban water system of Alexandria City, Egypt. *Journal of Cleaner Production* **18** (10–11), 1100–1106. doi:10.1016/j.jclepro.2010.02.009.

Martínez, C. I. P. & Poveda, A. C. 2022 The effects of environmental performance on competitiveness and innovation: a stochastic frontier approach for Colombia. *Environment Systems and Decisions* **42** (1), 51–62. doi:10.1007/s10669-021-09828-w.

Mendes, N. C., Bueno, C. & Ometto, A. R. 2016 Avaliação de Impacto do Ciclo de Vida: revisão dos principais métodos. *Production* **26** (1), 160–175. doi:10.1590/0103-6513.153213.

Milà i Canals, L., Chenoweth, J., Chapagain, A., Orr, S., Antón, A. & Clift, R. 2009 Assessing freshwater use impacts in LCA: part I – inventory modelling and characterisation factors for the main impact pathways. *International Journal of Life Cycle Assessment* **14** (1), 28–42. doi:10.1007/s11367-008-0030-z.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P. & Moher, D. 2021 The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *The BMJ* **372**, n71. doi:10.1136/bmj.n71.

Pfister, S., Koehler, A. & Hellweg, S. 2009 Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science and Technology* **43** (11), 4098–4104. doi:10.1021/es802423e.

Sahely, H. R., Kennedy, C. A. & Adams, B. J. 2005 Developing sustainability criteria for urban infrastructure systems. *Canadian Journal of Civil Engineering* **32** (1), 72–85. doi:10.1139/l04-072.

Sambito, M. & Freni, G. 2017 LCA methodology for the quantification of the carbon footprint of the integrated urban water system. *Water* **9** (6), 395. doi:10.3390/w9060395.

Shepherd, C. & Günter, H. 2006 Measuring supply chain performance: current research and future directions. *International Journal of Productivity and Performance Management* **55** (3–4), 242–258. doi:10.1108/17410400610653219.

Slagstad, H. & Brattebø, H. 2014 Life cycle assessment of the water and wastewater system in Trondheim, Norway – a case study. *Urban Water Journal* **11** (4), 323–334. doi:10.1080/1573062X.2013.795232.

Stanchev, P. & Ribarova, I. 2016 Complexity, assumptions and solutions for eco-efficiency assessment of urban water systems. *Journal of Cleaner Production* **138**, 229–236. doi:10.1016/j.jclepro.2016.03.113.

Van Zelm, R., Huijbregts, M. A. J. & van De Meent, D. 2009 USES-LCA 2.0 – a global nested multi-media fate, exposure, and effects model. *International Journal of Life Cycle Assessment* **14** (3), 282–284. doi:10.1007/s11367-009-0066-8.

Vilanova, M. R. N., Filho, P. M. & Balestieri, J. A. P. 2015 Performance measurement and indicators for water supply management: review and international cases. *Renewable and Sustainable Energy Reviews* **43**, 1–12. doi:10.1016/j.rser.2014.11.043.

Xue, X., Cashman, S., Gaglione, A., Mosley, J., Weiss, L., Ma, X. C., Cashdollar, J. & Garland, J. 2019 Holistic analysis of urban water systems in the Greater Cincinnati region: (1) life cycle assessment and cost implications. *Water Research X* **2**, 100015. doi:10.1016/j.wroa.2018.100015.

Yoshida, H., Christensen, T. H. & Scheutz, C. 2013 Life cycle assessment of sewage sludge management: a review. *Waste Management and Research* **31** (11), 1083–1101. doi:10.1177/0734242X13504446.

First received 10 January 2023; accepted in revised form 6 March 2023. Available online 16 March 2023