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Urban water supply and life cycle assessment

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Abstract

Guaranteeing drinking water access to populations living in urban centres is expected to become a significant challenge. This is due to threats such as climate change, deterioration of freshwater sources, and rapid urbanization. In order to minimize this negative prospect, urban centres should begin to update their water supply infrastructure, improve water distribution practices, or even implement the use of techniques such as desalination, advanced treatments for wastewater reuse, and rainwater harvesting. Life cycle assessment (LCA) is a commonly used tool to evaluate the environmental impacts, enable better decision-making among stakeholders and inform research on the topic. LCAs promote the evaluation of the environmental performance of systems, products, or services throughout their entire life cycle, translating inputs and outputs of resources, materials, energy, emissions, and waste into potential environmental impacts. However, the LCA of urban water supplies should be performed considering specific guidelines and the particularities of the local geography and water-related infrastructure. Finally LCAs should report a detailed interpretation of the results following a consistent framework. In this way, the outcomes from an LCA study can indicate best practices, interventions, or modifications necessary to decrease the environmental burdens associated with urban water supplies.

Keywords: sustainable development, LCA, integrated urban water management, drinking water treatment, pollution control.

Introduction

The adequate governance of water in many cities around the world is constantly being overlooked and, as a result, several of them currently experience all sorts of issues derived from excessive impermeabilization of riverbanks, lack of stormwater handling, and freshwater pollution. These issues should be addressed accordingly for the sustainable growth of urban centres (Arden and Jawitz 2019). Moreover, the availability of freshwater in proximity to several cities has been decreasing as a consequence of climate change, environmental neglect, and rapid urbanization, experienced mostly in developing countries (Larsen et al. 2016; Rodell et al. 2018). These issues end up impairing water security in many regions, and will soon require cities to ameliorate their urban water governance, in order to guarantee sufficient drinking water for their populations (Maurya et al. 2020). Besides conscientization for rational and efficient water use, improving urban water governance can be achieved by updating the current infrastructure, implementing the use of new water sources, or administering better treatment and distribution management practices (Silva et al. 2020; Gallego et al. 2008). However, their impacts should be evaluated and fully interpreted, with the aim of decreasing associated environmental burdens and improving their sustainability. For this purpose, life cycle assessment (LCA) is an increasingly adopted methodology.

The aim of an LCA is to compile all the inputs and outputs of resources, materials, energy, emissions, and waste associated with a specific product, system, or service during its whole life cycle, and then based on the data, estimate a diverse set of potential environmental impacts. In the context of urban water supply, the role of an LCA is to enable their evaluation based not only on performance indicators or benchmarking (Vilanova et al. 2015) but also on the quantification and interpretation of the use of resources and pollution shifts occurring during the entire life cycle of the processes, and fluxes associated with it. This is of great importance given the highly interconnected and environmentally fragile world we live in today. From the LCA perspective, the evaluation of environmental impacts of urban water supply involves aspects associated with the life cycle of electricity generation for water abstraction, treatment, pumping, and distribution; energy and heavy machinery for site preparation and pipes installation; concrete for the construction of dams and treatment plants; steel and other metals for equipment, pipes and pumping stations; chemical products used for water treatment; transportation of repair parts and chemicals products to the treatment plant; and recycling of water treatment equipment, etc.

The correct execution of an LCA enables a more complete picture of the environmental impacts associated with urban water supply. This is because the consideration of a set of potential life cycle environmental impacts and identification of their “hotspots” eases the decision-making about, for instance, what is the best water source to choose, or which treatment technique and distribution practice to adopt. An LCA is structured in four phases (ISO 2006). The first is the goal and scope definition, whereby the main purposes, system boundaries, assumptions and functional unit of the study are reported and justified. This is followed by the inventory analysis, when the processes and flows within the system boundaries are compiled, described and quantified in relation to the functional unit. The next phase is the life cycle impact assessment, performed with the use of software to model and calculate the potential environmental impact categories according to the chosen impact methodology. The impacts can be estimated and communicated either as midpoint categories (such as climate change potential, ozone depletion potential, eutrophication potential, and particulate matter formation), or endpoint categories (such as human health, ecosystem quality, and resource depletion), and can optionally include normalization, grouping, and weighting. The last phase is interpretation, although this is continuous throughout an LCA since it requires constant verification and reassessment.

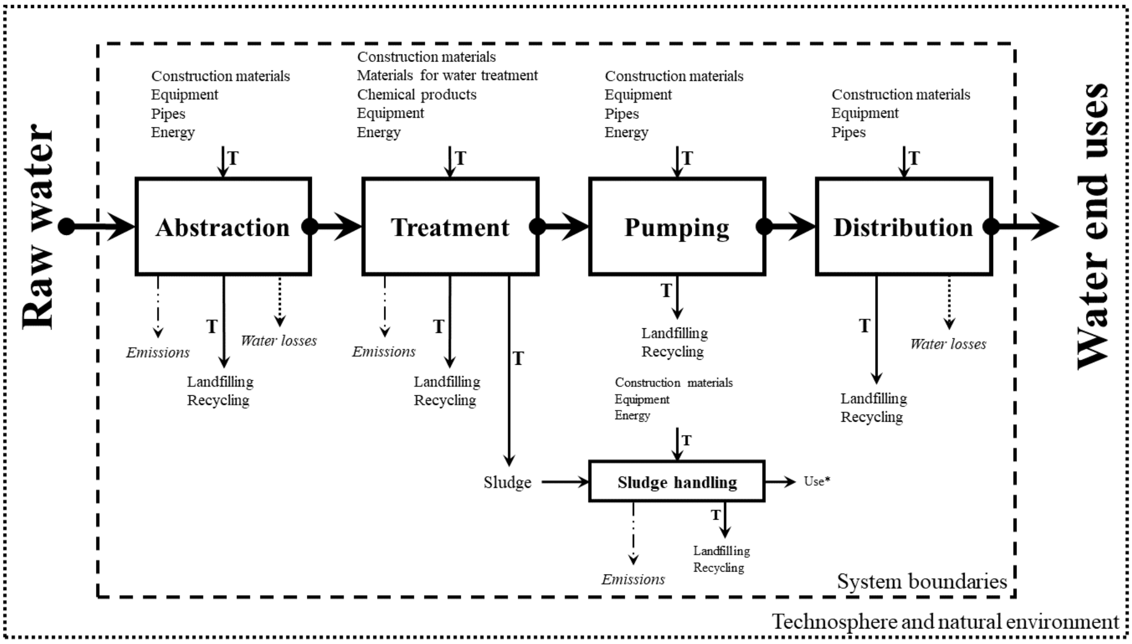
In this chapter the reader first finds an overview of the most important aspects regarding the application of an LCA in the evaluation of urban water supplies. Thereafter, the chapter explores some LCA studies about conventional urban water supply systems (treated freshwater delivered to consumers by centralized systems), and hybrid ones (those considering decentralized and alternative water sources). Finally, the chapter concludes with the main findings regarding the use of an LCA for the environmental performance of urban water supplies.

The application of LCA to urban water supply

The first scientific study applying an LCA approach to evaluate the environmental impacts of urban water supply dates back to the late 90's. Since then, the application of the LCA has constantly evolved. This is the direct result of more complete databases, developments in life cycle impact methodologies, and software tools for process modelling that became available to LCA practitioners over the years. However, several methodological inconsistencies and gaps can still be identified in the literature about the topic, and in due course they should be filled in order to produce a more satisfactory interpretation of the environmental burdens associated with urban water supplies. As previously mentioned in the introduction, the LCA methodology is structured in four phases according to the International Standards Organization (ISO 2006): goal and scope definition; inventory analysis; life cycle impact assessment; and interpretation. These are discussed next, in the context of the evaluation of urban water supply.

Goal and scope definition

The goal and scope definition is the first step of an LCA, and straight away it must provide key information about the study (e.g. its purposes, choices, assumptions, completeness, and ability to be representative), the system boundaries, and the functional unit. In the case of a conventional centralized urban water supply, the system boundaries refer to freshwater (surface and groundwater) abstraction, treatment, and pumping to the distribution network, as well as the maintenance required during their life cycles. It is common practice to depict these stages with further details in a process flow diagram (see example in Figure 1). Nonetheless, it is not uncommon that some stages or infrastructure parts are disregarded in LCA studies, albeit this can result in significantly underestimating the impacts in some categories (Igos et al. 2014). The functional unit is the quantitative basis on which the system is evaluated, and the environmental impacts are estimated. The most common units in the LCA of urban water supplies are the provision of 1.0 m^3 to the consumer, 1 capita/ year, and 1 city/year (Loubet et al. 2014). Although it is reasonable to estimate the impacts per unit of volume delivered to consumers, this can pose difficulties with interpretation in some cases since the initial and final water characteristics are often different, and the per capita consumption can vary widely. These are briefly commented on next.



T : transport. *Optional

Figure 1 General example of process flow diagram to describe conventional urban water supply in an LCA.

Even though potable water standards can be considered to have no significant variation, the quality of the raw water can be quite different. Consequently, the level of treatment necessary to achieve a potable standard (i.e. the treatment of good quality groundwater compared to polluted surface water or seawater desalination) also varies (Skuse et al. 2020; Flores-Alsina et al. 2010). Therefore, disclosure of the initial and final characteristics of the water being considered in the study is recommended. Another reason for this is that interpretation problems can arise when performing the LCA of water supplies augmented with non-potable water. For instance, cities enhancing their conventional urban water supply by blending treated wastewater (i.e. indirect potable reuse) do not necessarily need to meet drinking standards for the treated wastewater being reused (Lahnsteiner et al. 2018). Hence, it is important to carefully evaluate and describe these specificities during the goal and scope definition.

In relation to per capita water consumption, literature reports values of 14-538 L/day (IWA 2018). This wide range indicates that it is an important factor to consider when comparing the environmental performance of urban water supplies, especially between cities which have distinct socioeconomic and environmental backgrounds. This is especially true for studies considering alternative techniques in hybrid supply systems, such as wastewater reuse and rainwater harvesting (Sitzenfrei et al. 2017). Therefore, this information should be taken into consideration and reported during this phase, so that the interpretation becomes clearer for those consulting the study.

Inventory analysis

In this phase the inputs and outputs in each stage within the system boundaries are described and quantified according to the functional unit. A good starting point is to create an inventory table following the processes flow diagram, showing the final values corresponding to the functional unit for the foreground processes (i.e. the relevant energy, resources, materials, emissions, and waste flows gauged by the user – see

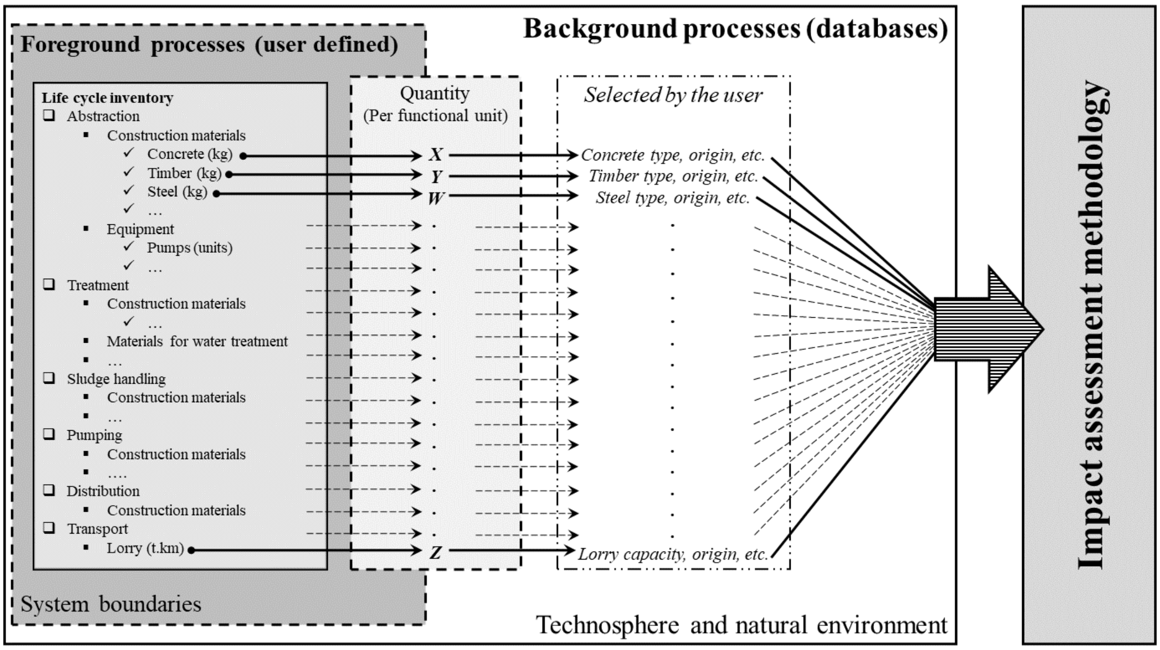


Figure 2). When data is not readily available (e.g. measurement is not possible or not publicly reported), they have to be estimated from literature values or using technical calculations. In all cases, the origins and logic behind the final results should be thoroughly discussed. Therefore, the main task here is to create the most complete and reliable inventory as possible in order to properly depict the urban water supply under study.

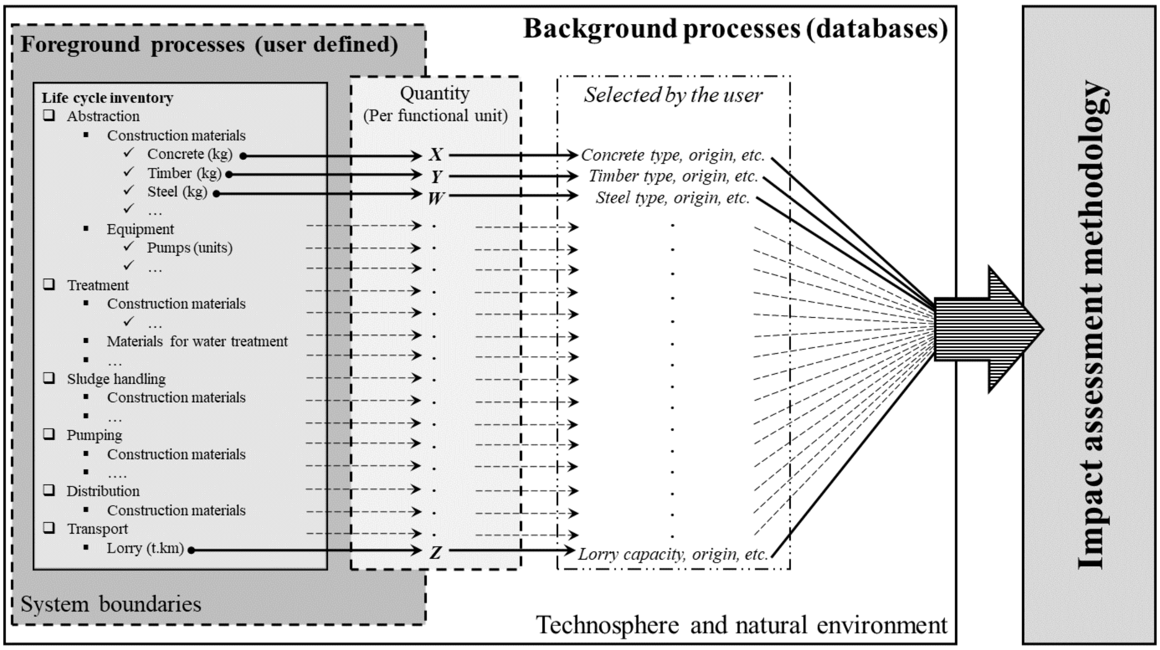


Figure 2 Scheme with the use of foreground and background processes for impact assessment of conventional urban water supply in an LCA.

The infrastructure necessary for urban water supply can be highly variable. This can be due to, for example, distance between the raw water source and the final consumer, local topography, amount of water to be distributed, and level of treatment necessary to achieve a potable standard. Another topic requiring closer consideration is water losses in the distribution network (AL-Washali et al. 2020), which can be responsible for a significant share of the environmental impacts (Del Borghi et al. 2013; Pillot et al. 2016) once it is directly related to the functional unit. Additionally, accurate electricity consumption is more than often the main task during this phase. Values from several locations worldwide suggest the energy intensity of these systems, conventional and hybrid ones, are usually in the range 0.20-4.90 kWh / m^3 (Wakeel et al. 2016).

The values included in the inventory are then used for modelling, when the foreground is connected to the corresponding background process using specific software such as Gabi, openLCA and SimaPro (see

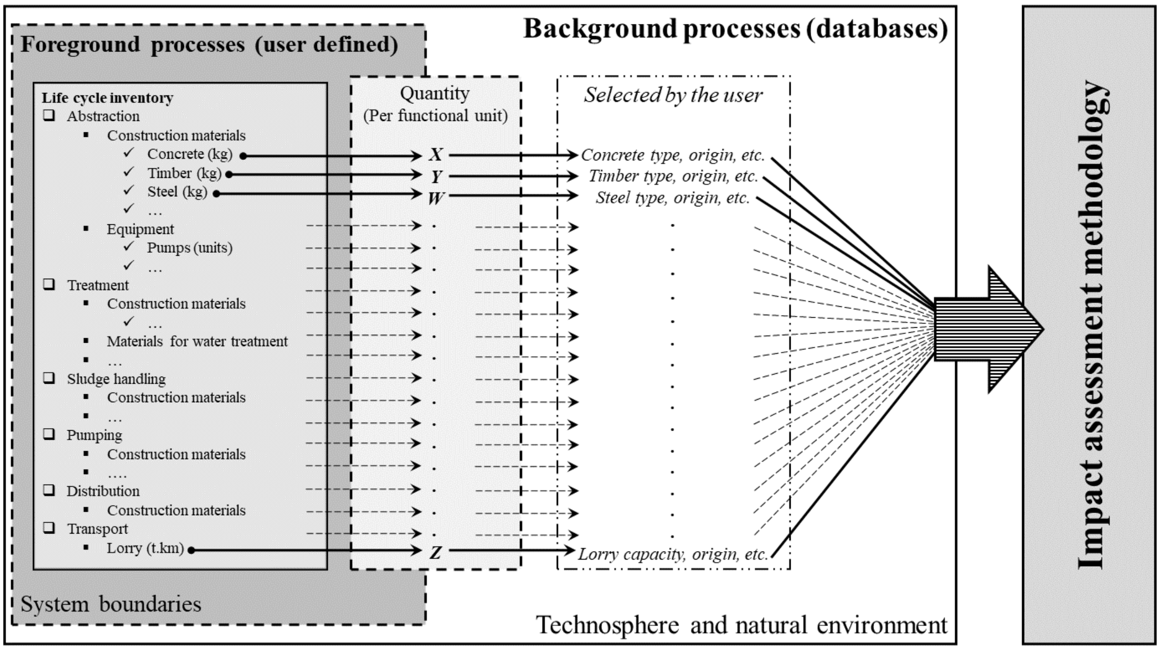


Figure *2*). The background processes are previously compiled data sets of inputs and outputs of resources, materials, energy, emissions, and waste over the life cycle of several thousand units or system processes. They represent a wide range of industries and services, including electricity generation, building materials, equipment, and chemical products used in the infrastructure, operation, and maintenance of urban water supply. The most common database used for the LCA of urban water supplies is Ecoinvent (Wernet et al. 2016). These days they are indispensable for estimating life cycle environmental impacts because they provide a more complete and standardized extension of the foreground processes, contributing to the completeness, ability to be representative, and reliability of LCA studies (Meron et al. 2016). Since there is a large number of processes to be chosen from by the user, the selected ones should correspond to the system under evaluation as much as possible. For instance, the electricity mix from the database should correspond to the location of the urban water supply infrastructure and the period within which the data was measured (Meron et al. 2016).

Impact assessment and interpretation

The aim of the impact assessment phase is to estimate, based on the information gathered for the inventory, the potential environmental impacts associated with the urban water supply. This is performed by software such as Gabi, openLCA and SimaPro. The most used impact assessment methodologies for the evaluation of urban water supplies are Eco-Indicator 99, CML, and ReCiPe (Loubet et al. 2014). An overview of these and other impact assessment methodologies can be found in the handbook by the Joint Research Centre Institute (JCR 2010). The most common midpoint impacts evaluated in LCA studies of urban water supplies are climate change, eutrophication, acidification, and ecotoxicity potentials. In relation to the first, Meron et al. (2016) reported values in the range of 0.16-3.4 kg CO_2 eq. / 1.0 m^3 of water supplied, with a mean of 0.84 kg CO_2 eq. / 1.0 m^3 and a median of 0.57 kg CO_2 eq. / 1.0 m^3. The discussion of endpoint categories, normalized results, and single-score indicators are also common in the scientific literature about the topic (Loubet et al. 2014; Byrne et al. 2017). This multitude of combinations among methodologies and discussion of impact categories often hampers interpretation by readers, which can impair literature comparison. LCA practitioners should therefore be aware of this when carrying out their studies.

The interpretation phase should include a discussion about the results of each impact category and details about their “hotspots” (i.e. the main contributors to that impact), check inconsistencies found during the study, and provide recommendations according to the goal and scope definition. It is important that this phase is discussed as a coherent, non-redundant, and logical follow-up from the main topics the study seeks to clarify. A guide containing more information about LCA results interpretation has been published by the Joint Research Centre (Zampori et al. 2016). Nevertheless, mixed results among impact categories are common in LCAs, and they should be more rigorously evaluated before a certain alternative or practice is recommended or options ranked. For this purpose, multi-criteria decision analysis (MCDA) can be applied for improving decision-making (Zanghelini et al. 2018). Additionally, uncertainty and sensitivity analysis are important tasks to be taken into consideration for interpretation and communication of LCA results.

Uncertainty refers to random or systematic errors (e.g. modelling choices, measurement inaccuracies or lack of scientific knowledge) relative to the system under study. Thus, uncertainty analysis refers to procedures that aim to quantify how these uncertainties are transferred to the LCA results. The most applied method for this in LCAs is the Monte Carlo technique. Sensitivity analysis is performed to obtain additional information to aid interpretation, as it quantifies the contribution of model parameters in the LCA result. It can be done locally, by varying a specific input at a time and checking its effect on the output result, or globally, by checking the contribution of each input during the propagation of several of them on the output result variance (Igos et al. 2019).

The LCA of urban water supplies

In this section there is a brief review of some relevant studies in the scientific literature about the LCA of urban water supplies. Initially, there are studies evaluating conventional urban water supply systems (centralized systems producing potable water only from freshwater sources), followed by others evaluating hybrid urban water supply systems (producing potable and non-potable water from seawater, wastewater, and rainwater). They are summarized in Table 1.

Table 1 Studies performing the LCA of conventional and hybrid urban water supplies

Reference	**Country**	**Goal of the study**	**Functional unit**	**Main conclusions**
Conventional systems				
(Tillman et al. 1998)	Sweden	To evaluate the environmental consequences of changes in the centralized wastewater treatments of Hamburgsund and Bergsjön.	Treatment of the wastewater from one person equivalent for one year.	It is beneficial to enlarge the system boundaries to evaluate wastewater and sludge treatments.
(Lassaux et al. 2007)	Belgium	To determine the environmental impact of using one cubic metre of water in the Walloon Region.	One cubic meter of water at the consumer tap.	The stages that contribute most to environmental impacts are water discharge, wastewater treatment plant operation and the sewer system.

(Lemos et al. 2013)	Portugal	To evaluate environmental impacts of the urban water system of Aveiro.	One cubic meter of potable water at the point of consumption.	The environmental impacts of the urban water supply are dependent on the local geography and cannot be extrapolated. Electricity consumption is the main hotspot.
(Slagstad and Brattebø 2014)	Norway	To examine the environmental impacts of operating the water and wastewater system in Trondheim.	The one-year provision of water, and collection, transportation, and treatment of wastewater (including stormwater).	The climate change potential of water supply is minor compared to the annual contribution of a person in Europe to this impact. Electricity consumption is a hotspot, contributing strongly to freshwater eutrophication.
(Barjoveanu et al. 2014)	Romania	To analyse the entire water services system in Iasi City and demonstrate the usefulness of the LCA to support water resources management.	One cubic meter of tap water delivered in the city.	The water supply generates more impacts than the wastewater treatment system because of its high energy demand and water loss in the distribution system. LCA is useful to analyse the environmental performance of water supplies.
(Jeong et al. 2015)	United States	To conduct the LCA of the centralized water system of the city of Atlanta.	One cubic meter of water distributed to the point-of-use.	The construction of the infrastructure is a significant contributor to the environmental impacts.
(García-Sánchez and Güereca 2019)	Mexico	To assess the environmental and social impacts of the water system in Mexico City and provide new perspectives for its sustainability.	One cubic meter of water for user consumption.	Electricity consumption for water treatment is the main contributor to climate change impact.
(Xue et al. 2019)	United States	To enable utility managers to make better decisions and highlight the importance of integrating water and wastewater management in the Greater Cincinnati region.	One cubic meter of treated and distributed meeting or exceeding National Primary Drinking Water Regulation.	Operation and maintenance are responsible for most of the energy consumption and climate change potential from water abstraction to its discharge. Infrastructure shows little contribution to impacts.
Hybrid systems				
(Lundie et al. 2004)	Australia	To examine Sydney Water's operation and its environmental impacts in the year 2021.	The provision of water supply and sewerage services in the year 2021.	Desalination increases the climate change potential of the system even when adding a little amount of water. An LCA is useful to assess financial, social, and local environmental issues of Sydney Water's operation in the future.
(Pasqualino et al. 2011)	Spain	To assess the operation of wastewater treatment in Catalunya and establish the environmental impacts of wastewater reuse.	One cubic meter of wastewater entering the wastewater treatment plant.	Reclaiming wastewater can be beneficial for non-potable uses. Potable wastewater reuse with tertiary treatment does not result in significant environmental improvement.
(Amores et al. 2013)	Spain	To use LCA to carry out the environmental impacts of the current system and of two scenarios for urban water cycle in Tarragona.	One cubic meter of potable water supplied to the consumers.	Energy consumption is the main hotspot, mostly for water distribution. Wastewater reuse scenario has similar impacts to the current water supply. Desalination should be used only in extreme drought scenarios.
(Lane et al. 2015)	Australia	To study the current water and wastewater services of	To provide water supply and wastewater	The wastewater treatment system contributes more to environmental

		the Golden Coast region using an LCA, with focus on the uncertainties.	management services during a one-year period to the urban population in the Gold Coast region.	impacts than the water supply. To further diversify water sources substantially increase the environmental impacts of the current water supply.
(Hsien et al. 2019)	Singapore	To inform stakeholders of the environmental impacts of NEWater and tap water delivered to consumers in Singapore.	One cubic meter of water (NEWater or tap water) delivered to the consumer.	The NEWater supply has a higher impact in three of the eight impact categories. The current water supply has a higher impact in the other five. Desalination promotes a disproportionately higher impact.
(Tarpani et al. 2021)	Brazil	To perform the LCA of three alternative techniques to substitute the use of drinking water from the distribution network in the north of Florianopolis.	To increase the availability of drinking water in the local distribution network by 1,000 cubic meters.	Indirect potable wastewater reuse alternatives had most of the lowest impacts in nine of the 15 categories assessed, and desalination most of the highest. An electricity mix other than Brazilian markedly increases the impacts from seawater desalination. Storage tanks are responsible for most of the life cycle impacts in rainwater harvesting.

LCA of conventional water supply

As far as the authors are aware, Tillman, Svingby and Lundström (1998) was the first study in the scientific literature to consider an LCA to evaluate the environmental performance of an urban water supply. However, the authors only briefly mentioned water treatment and distribution during the study since the focus was on the wastewater and sludge treatment stages of two Swedish municipalities. As a pioneer in LCAs, the work is mostly exploratory in terms of boundary choices and potential impacts derived from different choices for wastewater and sludge management. Almost a decade later, Lassaux et al. (2007) evaluated the impacts of supplying water to the Walloon Region (Belgium), besides wastewater treatment and its discharge to the environment. The water was abstracted from surface and ground water sources, and the authors provided information based on local data during inventory analysis. The authors considered the use of the Eco-Indicator 99 methodology and eight of its impact categories as well as including a sensitivity analysis on groundwater production infrastructure, diameter of sewerage pipes, and use of another impact assessment methodology (the CML). The authors concluded that wastewater treatment and its discharge stages generate higher impacts than the urban water supply and, therefore it should be the focus of eventual interventions.

The authors in Lemos et al. (2013) evaluated the urban water supply of Aveiro (Portugal). The raw water was sourced from a river located 25 km from the city, and groundwater. Water losses during the distribution stage were 38%. For the impact assessment, the authors considered eight ReCiPe 2008 midpoint impacts and its single endpoint indicator. Sensitivity analyses were carried out on several processes including water loss, electricity consumption, and use of chemical products. The authors found that electricity consumption was the main hotspot and discussed scenarios for the improvement of its environmental performance, such as decreasing water loss and the use of an electricity mix less dependent on fossil fuels. Additionally, the authors concluded that the results could not be extrapolated to other locations since it was found that the electricity consumption for water abstraction and treatment was much greater than those commonly found in literature, possibly due to its low system efficiency and local topography. Slagstad and Brattebø (2014) performed an LCA of the urban water supply in Trondheim (Norway). The water supplying the city is abstracted from a lake, treated, and distributed to consumers. The study provides a detailed description of the system, and the authors estimated that 32% of the water leaving the treatment plant was lost by the time it reached consumers. The impacts were assessed with eight normalized midpoint impact categories from the ReCiPe 2008 methodology, and a sensitivity analysis on the electricity mix was carried out. The main conclusion was that the climate change impact of the water supply was insignificant compared to the annual CO_2-eq emissions from a person in Europe.

Barjoveanu et al. (2014) performed an LCA of the urban water supply and the wastewater treatment system of Iasi city (Romania). The water was abstracted from surface water located several kilometres away from the city, and groundwater. The electricity consumption of the system in peak hours reached 0.35 kWh/m^3, and water loss during distribution was 41%. The authors considered ten normalized midpoint categories from the CML 2000 methodology, and a single score indicator from Ecological Scarcity 2006. Their conclusion was that for all categories, except those related to water pollution in the two impact methodologies, the water supply system had the highest impacts when compared to the wastewater treatment system. This was attributed mostly to the water losses during distribution. A year later, Jeong et al. (2015) performed an LCA of the urban water supply and wastewater treatment systems of the city of Atlanta (USA). The raw water was sourced from a river adjacent to the city and treated by coagulation/flocculation and filtration before distribution (with water loss at this stage being 13%). The authors provided a detailed inventory analysis, based on public information from local authorities. For the impact assessment, ten midpoint impacts from the TRACI v2.1 methodology were used. The main finding was that the infrastructure construction was a significant contributor to environmental impacts, although the life cycle datasets used for steel and cast-iron production were taken from Europe since they were not available for the USA at the time.

More recently, García-Sánchez and Güereca (2019) used an LCA to evaluate the environmental impacts of the urban water supply in Mexico City (Mexico), which is mostly sourced from groundwater, with the rest originating from surface water. The authors estimate that about 40% of the water was lost during distribution and they did not consider any infrastructure for the system. The impact assessment was performed with seven midpoint impacts from the ReCiPe v1.12 methodology, and uncertainty analysis was carried out based on the Monte Carlo approach. The main conclusion was that the environmental impacts of pumping water from source to its treatment was the main hotspot due to the high electricity consumption and the national electricity mix being heavily based on fossil fuel. Lastly, Xue et al. (2019) used two different methodologies to estimate the life cycle environmental impacts of the urban water supply and wastewater treatment of the greater Cincinnati region (USA). The water was sourced from the Ohio river, and 19% of it was lost during distribution. The data for the system was derived from the local water utility, and the authors considered the TRACI v2.0 methodology for the impact assessment as well as the ReCiPe 2008 for metal and fossil fuel depletion potentials, and performed sensitivity analyses on several input parameters including the electricity mix. The results indicated that energy consumption for water distribution was mainly responsible for the impacts, and that infrastructure had little contribution except for metal depletion potential.

The LCA of hybrid water supplies

The first LCA in scientific literature considering an alternative and decentralized option for urban water supply was Lundie et al. (2004). The study created scenarios to represent the water supply situation for Sydney (Australia) in the year 2021, including demand management initiatives, higher efficiency pumps, and desalination. In relation to the latter, the construction and operation of a reverse osmosis seawater plant was chosen to supply 6% of the city's water consumption. The environmental impacts were assessed using seven midpoint indicators, including climate change, eutrophication, and human toxicity potentials. The results showed that if desalination was implemented in the city, the environmental burdens of supplying water would increase substantially. A few years later, Pasqualino et al. (2011) evaluated several options for wastewater reuse aiming to decrease the environmental burdens of supplying water to the region of Catalunya (Spain), albeit most of the study was focused on the wastewater treatment stage. The authors considered nine midpoint categories from the CML 2000 methodology to analyse the environmental impacts of four scenarios: treated wastewater discharged into the environment, secondary treated wastewater used for brine dilution, tertiary treated wastewater used for potable uses, and tertiary treatment wastewater for potable use instead of desalinated seawater. The authors concluded that reusing wastewater for non-potable uses was environmentally beneficial, whilst for potable uses it was not, and desalinated water should only be used for potable uses due to its high energy consumption.

Still in the Catalunya region, Amores et al. (2013) performed an LCA of the urban water supply of Tarragona. The authors used actual operational data from the city of 145,000 inhabitants provided by internal reports, interviews, and previous studies in the region. In addition, the authors evaluated two scenarios: wastewater reuse for agricultural purposes after tertiary treatment, and its combination with reverse osmosis seawater desalination providing 25% of the water consumption. Seven midpoint categories from the CML 2001 methodology were used for the environmental impact assessment. The main findings were that electricity for water abstraction and distribution were major hotspots, and wastewater reuse can increase water availability in drought situations without increasing environmental impacts - desalination should only be used as a last resource. Lane et al. (2015) assessed the environmental impacts of increasing the adoption of residential rainwater harvesting, indirect potable wastewater reuse, and seawater desalination in the urban water supply in the Gold Coast region (Australia). The scenario built to evaluate this was rainwater harvesting systems corresponding to 15%, desalination to 29% and wastewater reuse to 10% of the water being supplied to the region, and the remaining amount from the reservoir. The inventory was created from compiled information of locally or regionally measured data with available empirical and literature values, and the impact assessment was made with 14 midpoint categories from the ReCiPe 2008 methodology. The results from the LCA study suggested that diversifying the water supply in the region would substantially increase the environmental impacts of the system.

Recently, Hsien et al. (2019) evaluated the water supply of Singapore, which encompasses several subsystems supplying water to households and industries. It includes different wastewater reuse options for non-potable reuse in industries, and for augmenting the main supply system composed of surface water (from river and reservoirs) and seawater desalination. The water loss in the distribution system was 5%, and the desalination technology considered was reverse osmosis. The authors evaluated the water supply using eight midpoint impacts from the ReCiPe 2008 methodology and considered sensitivity analysis for different combinations of water sources. The results showed that although desalinated water corresponded to about a fifth of the water consumption, it was responsible for one third of the climate change potential of the system. The wastewater reuse scheme for non-potable uses in industries had the highest impacts in three of the eight impact categories and the main water supply in five of them. Finally, Tarpani et al. (2021) performed an LCA study comparing three alternatives for increasing the urban water supply in Florianopolis (southern Brazil). The options were seawater desalination by reverse osmosis, an indirect potable wastewater reuse scheme by upflow anaerobic sludge blanket digestion (UASB), oxidation ditch and ozonation followed by soil aquifer treatment

(SAT), and five different types of rainwater harvesting systems. The authors considered 15 midpoint impacts from the ReCiPe 2016 methodology for result interpretation and included a parametric analysis on key aspects of each alternative. Additionally, a sensitivity analysis was undertaken on the climate change potential from the emissions of CH_4 and N_2O of the wastewater treatment stage in the wastewater reuse alternative, and of the electricity mix. The results indicated that desalination and wastewater reuse had electricity consumption as the main contributor to impacts, whilst for rainwater harvesting it was storage tanks. The climate change potential of wastewater reuse showed highly variable results, from 0.7-1.3 kg CO_2-eq / m^3. Overall, however, this option showed the lowest impacts in nine categories.

More information about alternative techniques that can be used for hybrid water supply can be found in the literature dedicated to the topic. For instance, for desalination and LCA see Tarpani et al. (2019), Aziz and Hanafiah (2020), and Lee and Jepson (2021); for wastewater reuse and LCA see Tarpani and Azapagic (2018), Gallego-Schmid and Tarpani (2019), Corominas et al. (2020), and Risch et al. (2021); for rainwater harvesting and LCA see Zanni et al. (2019) and Ghimire et al. (2017).

Conclusions

There has been a considerable number of LCA studies about conventional urban water supplies published in the last two decades. Moreover, alternative techniques that can be adopted for augmenting urban drinking water availability such as desalination, advanced treatments for wastewater reuse, and rainwater harvesting are also being increasingly evaluated using LCA. This is of great importance given the negative consequences of climate change, freshwater deterioration, and the rapid urbanization already experienced in some cities, especially those in the developing south. The findings from these

LCAs assist researchers and stakeholders to understand and minimize the environmental impacts associated with urban water supply.

LCA studies on conventional urban water supplies suggest they usually have a climate change potential below 0.60 kg CO_2-eq. per 1.0 m^3 delivered to customers. Variations occur mostly due to differences in local geography, infrastructure requirements, and water losses during distribution, as well as the electricity mix of the region. Estimates for other impact categories are more complex to define due to a diversity of frameworks adopted by LCA practitioners, including system boundaries, assumptions, databases, and impact assessment methodologies. A more complete description of the life cycle inventory and more sound discussion of environmental impacts, including uncertainty analysis on the most influential parameters (such as electricity consumption and water losses) are welcome. These are important aspects that need to be discussed and eventually fulfilled by LCA practitioners in the future to enable a homogenous and robust evaluation of the life cycle environmental performance of urban water supply.

A trend has been observed over recent years in the application of LCAs from conventional to hybrid urban water supplies. This suggests preoccupation not only about urban water availability, but also in relation to the environmental consequences of the adoption of alternative water sources. However, the use of LCAs to evaluate alternative and decentralized techniques for water supply must be carefully conducted, taking into consideration the quality of the final effluent and other details that can impair the correct interpretation by LCA practitioners and stakeholders. More specifically, efforts towards promoting an easier comparison in terms of their purposes, assumptions, life cycle inventory description, and impact assessment methodologies are necessary when evaluating these hybrid systems. These would greatly improve the results interpretation and decision-making processes by stakeholders and promote a more resilient and sustainable urban water supply.

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