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LIFE CYCLE ASSESSMENT OF WATER AND WASTEWATER TREATMENT SYSTEMS: AN OVERVIEW

BY

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Abstract. Given the urgent need for reliable assessment instruments that can contribute to decision making processes within sustainable water resources management and reported capabilities of the Life cycle assessment (LCA) in this field, this paper presents the state-of-art regarding LCA methodology use in the analysis and evaluation of water supply and wastewater treatment systems.

The literature review has shown that the use of current LCA methods are mainly focused on comparing the environmental impacts of existing or projected water and/or wastewater treatment tchnologies. The majority of these studies have focused on the energy consumption of various treatment technologies, and especially of the membrane processes.

The LCA use in analyzing water services systems has grown significantly in the last years, but there are still some issues that can be improved including economic indicators and refining the impact categories by developing appropriate indicators and weighting scales for a true and reliable life cycle impact assessment.

Key words: LCA, water supply systems, wastewater treatment systems.

1. Introduction

Water is one of the critical resources for sustainable development, both by its position and resource base due to its crucial role in eradicating poverty and its importance to the development of industry, agriculture, services, energy production, biodiversity and people’s health. This is already accepted and assumed by most of the governments trough the adoption of the Millennium Development Goals which are closely linked to sustainable water resource management.

For adapting to the ever pressing water related problems (population growth, climate change, urbanization, economic and industrial development, etc.), water resources management has to evolve into a multi-stakeholder, interdisciplinary process that ensures sustainable water use together with the conservation of water resources and of sensitive aquatic biodiversity [1], [2]. Furthermore, although there are global concerns in this regard, most problems related to sustainable water resources management are reflected at the local level of the small communities' and individual industrial users. These aspects bring forward the growing need to create and implement tools to clearly address and contribute to solving emerging issues on water resources for the future generations.

In this context, measurement instruments that are capable to identify and quantify the impacts of fresh water use are of great importance. Such instruments should generate information on assessing impacts and developing solutions by water suppliers, users or regulators, providing thus a support for decision making in sustainable water resources. This is the main idea underlying a complex research project that is currently implemented in Romania by a consortium of 4 universities under the coordination of the "Gheorghe Asachi" Technical University of Iaşi. The Technical and Decision Making Support System for Sustainable Water Management - STEDIWAT project has as the main objective to develop a support system that will provide a scientific base for the decision-making processes and will contribute to knowledge transfer, regional, national and international cooperation of stakeholders and implementation of the Integrated Water Resources Management in Romania [3].

One of the most intensively used tools for the assessment of environmental impacts is the Life Cycle Assessment (LCA) which is generally employed for measuring the impacts of various products and production processes across their entire lifespan [4].

However, although LCA has grown into a mature and successful instrument for consumer products and various production processes, LCA is still lacking comprehensive approaches to evaluate the environmental impacts associated with the water cycle management (water treatment, use and wastewater treatment) [5], [6]. Traditionally, water resources are regarded in most of the LCA reports and studies as a transport medium for useful products or pollutants for most of the studies, the impact of water resources use being considered just as water consumption, while the water quality issues are considered to a lesser extent. This approach of LCA studies is due to the fact that the LCA methodology was developed in countries that historically have not faced water scarcity issues [7], but also because there is a difficulty within the LCA methodology related to water resource classification [8], [9], because water is the only abiotic resource natural resource that is renewable and finite at the same time.

There are far fewer studies available in the LCA literature that focus on water as a product, defined by clear characteristics, or as a result of a production process which causes various impacts on the environment, as presented in Fig.1.

Bearing in mind the urgent need for reliable assessment and analysis instruments that can contribute to decision making processes within sustainable water resources management, as well as the reported capabilities of the LCA methodology in this field, this paper aims at presenting the state-of-art regarding LCA methodology use in the analysis and evaluation of water supply and wastewater treatment systems.

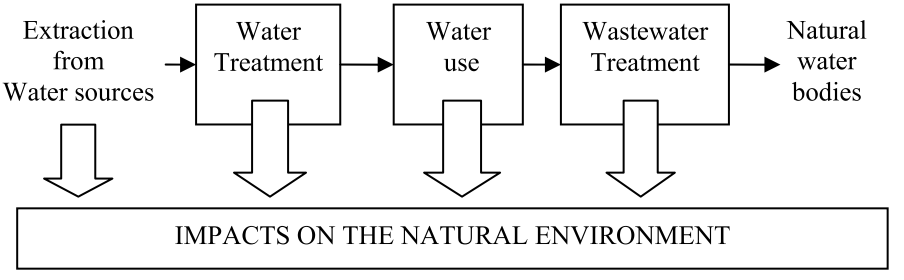

Fig. 1 − The water use cycle.

2. Life Cycle Assessment Methodology

Life cycle assessment (LCA) is an ISO 14040 standardized method for the environmental assessment of industrial systems from “cradle-to grave”. The “cradle-to-grave” approach begins with the extraction of raw materials from the earth, continues with product development and manufacturing, and finally ends when all materials are returned to earth. LCA evaluates the environmental aspects of a product or service through all these life cycle phases, thus allowing coherent comparison between different schemes providing the same service or “function” [10].

Based on the ISO 14040 [11] the LCA standards series uses the following steps Fig. 2:

1. *Goal and scope definition*: identifying the LCA's purpose and the expected products of the study, and determining the boundaries and assumptions based upon the goal definition;

2. *Inventory analysis*: performing mass and energy balances to quantify all the material and energy inputs, wastes and emissions from the system, i.e. the environmental burdens;

3. *Impact assessment*: aggregating the environmental burdens quantified in the Inventory Analysis into a limited set of recognized environmental impact categories, such as global warming, ozone depletion acidification, etc.;

4. *Interpretation*: using the results to reduce the environmental impacts associated with the product or process [12].

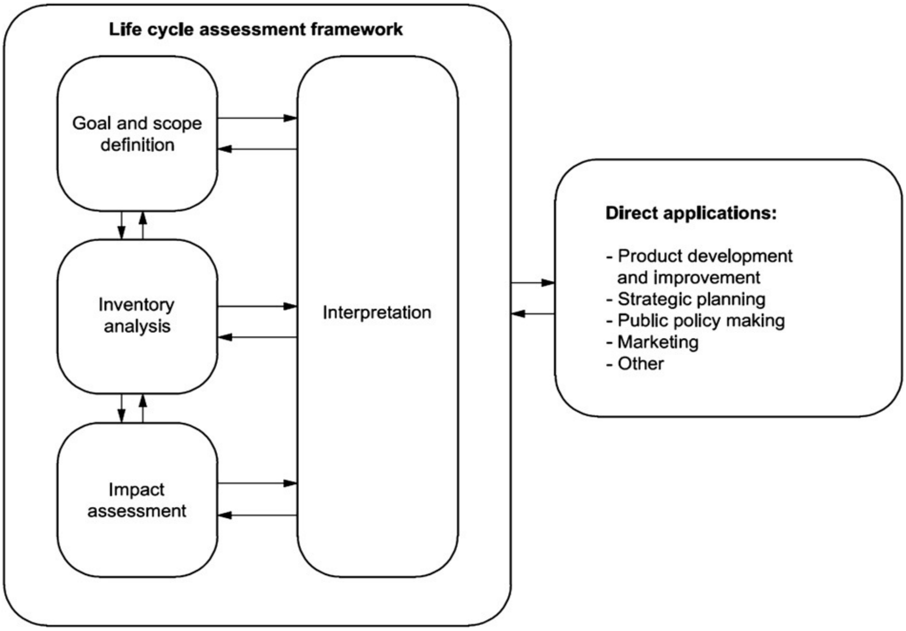

Fig. 2 − The LCA-framework according to ISO 14040 standard.

One of the most important steps in LCA is the impact assessment which measures the damages caused on various environmental components and aspects. To date, there are available numerous approaches towards the life cycle impact assessment (LCIA) which can be used including with the help of software programs (Gabi, SimaPro, Umberto), that enable users to develop, store, analyze and exchange vast amounts of data related to products, services, processes, and their respective impacts. The most important LCIA methodologies, which are also used for water related LCA studies are:

The Eco-indicator 99 method offers a way to measure various environmental impacts, and shows a final result in a single score. Normalization and weighting are performed at damage category level (endpoint level in ISO terminology). Three damage categories are used: 1) Human Health, 2) Ecosystem Quality, 3) Resources. Damage assessment step means that the impact category indicator results that are calculated in the Characterization step are added to form damage categories [13].

CML 2 baseline method (2000) provides a list of impact assessment categories grouped into obligatory impact categories (Category indicators used in most LCAs), additional impact categories (operational indicators exist, but are not often included in LCA studies), other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA) [14].

The Environmental Development of Industrial Products (EDIP) was developed by the Institute for Product Development (IPU) at the Technical University of Denmark. The midpoint approach of EDIP 1997 covers almost all the emission-related impacts, working environment impacts and resource use [15].

The vast majority of LCA studies regarding water, wastewater or sludge treatment systems have employed the aforementioned LCIA methods, as also presented in Table 1 [16].

Table 1
LCIA Methods Used in Water, Wastewater or Sludge Treatment Systems Related LCA Studies

Method	Developer	User (Reference)
CML	Centre for Environmental Studies (CML), University of Leiden	Roeleveld *et al*. [17], Agence de l'Eau Rhin-Meuse [18], Khalifa *et al*.[19], Pillay *et al*. [20], Suh and Rousseaux [21], Beavis and Lundie [22], Vlasopoulos *et al*. [23]
Eco Indicator 99	PRé consultants, the Netherlands	Houillon and Jolliet [24], Rihon [25]
EDIP	Institute for Product Development (IPU), Technical University of Denmark	Clauson Kaas *et al*. [26]

3. LCA of Water and Wastewater Treatment Systems

Using LCA for the environmental and economical evaluation of existing or projected water and wastewater systems is particularly challenging, because of the difficulty of properly delimiting the system boundaries, on one hand, and on the other hand because of the difficulty of classifying water resources. In this section, we present an overview of the scientific efforts to study the water services systems through an LCA approach, focusing on water treatment, water use and wastewater treatment systems.

3.1. LCA for Water Production Evaluation

The discourse regarding the use of LCA for evaluating the water treatment technologies stems from the need to include environmental criteria beside the technical and economical ones in choosing feasible treatment technology alternatives for water pollution. In this respect, most of the LCA studies regarding water treatment have focused onto employing LCA methods to determine the environmental impacts of various water treatment technologies, and especially for evaluating membrane processes (which by their nature can be energy intensive), as presented in Table 2.

Table 2
LCA Studies on Water Production

Research group	LCIA method/ Software	Study objectives and results
Sombekke *et al*., [27]	Ecoindicator 99 LCAqua (based on SimaPro)	Comparison of conventional treatment plant (clarification, filtration, disinfection, GAC adsorption) with nanofiltration membrane process. The highest impacts were obtained for electricity consumption and GAC regeneration.
Mohapatra *et al*., [28]	Ecoindicator 99 LCAqua (based on SimaPro)	Comparison of conventional treatment plant (as previous) with a two-step RO plant. The two plants have scored similar impacts, also electricity consumption and GAC regeneration have proven to be the most important environmental aspects.
Beavis *et al*., [22]	CML Gabi	Comparison of disinfection alternatives.
Friedrich *et al*., [29]	CML Gabi	Comparison of conventional treatment plant *vs*. ultrafiltration plant.
Vince *et al*., [10]	IMPACT 2002+ Gabi	LCI modeling of unitary treatment steps.
Raluy *et al*., [30] Raluy *et al*., [31] Raluy *et al*., [32]	Eco-Indicator 99 Eco-Points 97 CML SimaPro	Comparison of desalination technologies (multi-stage flash distillation, Multi-efects distillation and RO). Influence of different energy sources (electricity and heat) on the impacts of these desalination technologies.
Stokes and Horvath 2006 [33]	EIO-LCA (Economic Input-Output) WEST (Gabi)	Focus on energy use impacts of water supply systems (desalination, transfer and reuse).
Stokes and Horvath, 2009 [34]	EIO-LCA (Economic Input-Output) WEST (Gabi)	Hypotetical comparison study of different desalination options (Conv. Pretreatment-DES; MF-UF-DES; Desalination of brackish groundwater; recycling wastewater for nopotable use.

The first two studies presented in Table 2 focus onto the comparison of various treatment technologies by using a dedicated software – LCAqua, designed by KIWA Research and Consultancy, but this tool focuses onto the use phase of the water treatment facilities and do not take into account the construction and decommissioning of these facilities. Friedrich *et al*., [29] has included the impacts of these two stages and has found out that the construction phase accounted to less than 15% of the total plant impact, while the decommissioning phase impacts were negligible to less than 1%. Furthermore, Beavis *et al*., [22] has focused on quantifying the overall impacts of various water treatment plant employing different disinfection technologies, while Vince *et al*., [10] have proposed a much detailed approach by determining the impacts of each unit operation within a water treatment facility with a focus on energy consumption.

More recently, attention has been paid to the study of the impacts of desalination projects. Thus, Raluy *et al*., [30],…,[32] have studied different desalination technologies, as well as the impact of various energy sources. Stokes et al have developed a new LCA approach for the study of water systems in which economic data are combined with resource consumption and environmental emission and waste data (*e.g*., energy use, toxic air emissions, hazardous waste) and have incorporated this into a MS-Excel based tool, called WEST – Water Energy Sustainability tool that can evaluate the construction, operation and maintenance of water systems. They have used this tool to evaluate from an energy and air emmission perspective, different water supply options [33] or different desalination options [34] and have concluded that the results are site-specific.

The main conclusion of the literature on water production’s impacts by LCA is that electricity production for plant operation is the main source of impacts, but there are serious drawbacks in comparing the results of various studies, since most of them were developed considering site specific assumptions. In fact, the lack of an unitary LCA approach for water production evaluation and the scattering of impact data of these technologies represent the most important issues in promoting LCA as a solid and reliable tool for water production assessment and decision making.

3.2. LCA for Wastewater Treatment Plants

Wastewater treatment systems have been designed and operated to control water pollution and minimize the environmental impacts of industrial and domestic wastewater discharge, but, however, wastewater treatment systems consume energy and chemical reagents, while produce sludge and various emissions. Different options of wastewater treatment have different performance characteristics, as well as distinct direct effects on the environment [35] which may occur at various steps in a WWTP’s lifecycle.

LCA has been used to explore the sustainability of wastewater treatment systems mostly to compare with different conventional treatment processes [36]. Some works focused more on the construction and demolition of wastewater treatment plants (WWTP) than on their operation [37] while other studies focused on parts of the wastewater treatment systems and used LCA to investigate treatment alternatives and different unit processes.

Recently, wastewater treatment systems have received much more attention from the LCA scientific community, research being carried out on both small and large wastewater systems, in order to assess the impacts of tertiary treatment steps, wastewater reuse technologies, or sludge management, as presented in Table 3.

Table 3
LCA Studies on Wastewater Treatment Plants

Reference	LCIA method (Software platform)	Study objectives and results
Gallego *et al*., [38]	CML2000 SimaPro 6.0	Evaluation of 13 wastewater treatment plants WWTPs) of small communities located in Galicia (NW Spain).
Meneses *et al*., [39]	CML 2000	Evaluation of different disinfection treatments (chlorination plus ultraviolet treatment, ozonation and ozonation plus hydrogen peroxide) and to assess the environmental advantages and drawbacks of urban wastewater reuse in non-potable applications.
Munoz *et al*., [40]	USES-LCA EDIP97	Comparison of different scenarios involving wastewater reuse, with special focus on toxicity-related impact categories.
Ortiz *et al*., [41]	CML 2 baseline 2000, Eco-Points 97 Eco-Indicator 99 SimaPro5.1	Comparison the environmental impact of several membrane technologies for wastewater reclamation, including the indirect toxicity contribution from energy and infrastructure.
Tangsubkul *et al*., [42]		Assessment membranes and stabilisation ponds as reclamation technologies, including toxicity of trace pollutants in biosolids management.
Wenzel *et al*., [43]		Assessement ozonation, sand filtration, and membranes, taking into account the toxicity of some priority and emerging pollutants in wastewater.
Johansson *et al*., [44]	Boliden, Econova, Ragn-Sells Aqua Reci	Sewage sludge handling with nutrient utilization.
Houillon G., *et al*., [45]		Comparison of 6 wastewater sludge treatment scenarios, focusing on energy and global warming potential.
Zhang Q.H., *et al*., [46]	process-based LCA combined with input–output based LCA	Application of LCA for an evaluation of wastewater treatment by combining the process-based LCA and the input–output based LCA in one framework.

Furthermore, recent studies have focused on developing new LCA methodologies that include cost – benefit analysis and economic impacts of wastewater treatment systems [46], [47] by combining economic input-output (IO) data with process-based life cycle Inventories.

The results of recent studies reported by [43],...,[45], highlight the importance of including wastewater pollutants in LCA of wastewater systems assessing toxicity, since the contribution of wastewater pollutants to the overall toxicity scores in this case study can be above 90%.

Although recently the scientific community has approached the impacts of wastewater treatment plants from an LCA perspective more thoroughly and with very diverse scopes, there are still some limitations related to the use of LCA in this field. As in the case of water production sector, the wastewater treatment studies engage a multitude of methodologies, impact categories and site specific assumptions that make study comparison and correlations almost impossible. Furthermore, LCA has been reported as a very complex and time-consuming methodology, that does not always account for all the environmental impact and to a far lesser extent the economic impacts of various wastewater treatment alternatives.

3.3. LCA and Water Services Systems

Water service systems have received far lesser attention within the LCA community as compared to their systems components: the water production, water distribution and wastewater systems. This is due to the major drawback of employing LCA to study wastewater systems is the difficulty of determining the systems boundaries and their scale [48], and the complexity of such a study. Anyways, there are some attempts at analyzing the water cycle management in a systemic way, as presented in Table 4.

Table 4
LCA in Water Systems Planning and Analysis

Researcher	Study objectives and results	Case study location
Lundie *et al.*, [6]	Comparison and projection (2021) of relative sustainability of water services components under different scenarios, including	Sydney, Australia
Tarantini and Ferri [49]	Comparison of impacts of water services	Bologna, Italy
Lassaux *et al.*, [50]	Determination of the environmental impact of using one cubic metre of water from the pumping station to the wastewater treatment plant.	Walloon Region, Belgium

Lundie *et al*., [6] studied Sydney's plan for providing water and sewer services in 2021 (using the Gabi software and the CML LCIA method) and showed that water distribution and wastewater treatment generated more impacts than the water treatment process.

Tarantini *et al*., [49] studied Bologna's domestic water supply system with different LCIA methods (CML 92, CST 95, USES 1998). The results have shown that contrary to the previous study, the impacts of producing potable water were greater than those of the wastewater treatment plant (WWTP) because of the high electricity consumption for potable water plant intake pumping.

Lassaux *et al*., [50] has analyzed the impact of producing and using 1 m^3 of water, by studying the building and operation of the following processes: Water catchments (from ground and surface waters), Water treatment, Water supply, Sewer system, Collective and individual wastewater treatment plant, Wastewater sludge treatment, Water discharge (without treatment). The study concluded that the major environmental impacts are caused *after the tap,* that is during the wastewater collection, transport and treatment.

4. Conclusions

Recently, the LCA methodology has been more and more employed as a decision support tool in sustainable water management, providing useful information on the various environmental impact of existing or projected water related infrastructure and processes. The LCA community has struggled to use existing LCA methodologies, models and databases in comparing the impacts of various water, wastewater and sludge treatment technologies, and to a lesser extent to analyze, from an LCA perspective the overall water services system.

This study shows that employing LCA in analyzing water systems is particularly difficult due to the following reasons: (1) system complexity and difficulty in determining the system boundaries, (2) LCA methodology complexity and data availability issues. Most of the reviewed LCA studies are based on site specific assumptions with different choices for the LCA system limits and for the LCIA method (CML, Eco-indicator 99, etc.) and, with few exceptions, most of the reviewed studies have not accounted for the impact of the LCIA method on the LCA results.

Concluding, the LCA use in analyzing water services systems has grown significantly in the last years, but there are still some issues that can be approached to further improve this field of research, for example: developing LCA methodologies that include economic indicators in assessing the performance of water systems, refining the impact categories by developing appropriate indicators and weighting scales for a true and reliable environmental impact assessment.

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EVALUAREA CICLULUI DE VIAȚĂ PENTRU SISTEME DE TRATARE ŞI EPURARE

(Rezumat)

Datorită nevoii urgente pentru dezvoltarea unor instrumente de analiză eficiente pentru managementul durabil al resurselor de apă, precum şi datorită performanțelor evaluării ciclului de viață (ECV), această lucrare prezintă stadiul actual al cercetărilor privind utilizarea acestei metodologii în analiza şi evaluarea sistemelor de tratare şi de epurare ale apei.

Analiza literaturii de specialitate a arătat faptul că metodele ECV sunt în prezent utilizate pentru compararea impacturilor de mediu ale diverselor tehnologii de tratare şi/sau epurare. Majoritatea acestor studii au avut în vedere analiza consumului de energie pentru diverse opțiuni tehnologice de tratare/epurare şi în special pentru procesele de membrană. Mult mai puține studii ECV au fost realizate pentru analiza sistemelor complete de furnizare/utilizare şi epurare a apei.

Utilizarea ECV în analiza managementului resurselor de apă a cunoscut o dezvoltare puternică în ultimii ani, însă mai sunt câteva aspecte care pot fi îmbunătățite, de exemplu: includerea de indicatori economici sau revizuirea categoriilor de impact prin dezvoltarea de indicatori şi factori de importanță care să conducă la o evaluare corectă şi eficientă a impacturilor asupra mediului.