Environmental performance evaluation of a drinking water treatment plant: A life cycle assessment perspective

ENVIRONMENTAL PERFORMANCE EVALUATION OF A DRINKING WATER TREATMENT PLANT: A LIFE CYCLE ASSESSMENT PERSPECTIVE

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Abstract

Drinking water treatment aims to avoid or minimize some risks to human health and to provide adequate water quality by removing physical, chemical and biological contaminants. However, treatment processes require increasing efforts in terms of technology, chemicals and energy inputs, which generate increased secondary environmental impacts and added water production costs. The objective of this study is to evaluate the drinking water treatment plant (DWTP) in Iasi City (Romania) by life cycle assessment (LCA) and to identify and characterize its environmental impacts. Iasi DWTP involves the following scheme: pre-oxidation (chlorine dioxide), coagulation/flocculation, sedimentation, pH correction (calcium hydroxide), rapid sand filtration, granular activated carbon filtration and disinfection (chlorine gas). LCA was performed according to the ISO 14040 standard with the support of SimaPro 8.3. software and Eco-invent 3.3 data base. Life cycle impact assessment has been performed with Recipe 1.13. Midpoint method. The life cycle inventory included the construction and operational phases. The novelty of this study was to define two additional functional units related to removing contaminants besides the traditional 1 m^3 of treated water. The main contributors to impact in most categories were the electricity consumption (25 – 95% depending on impact category) and the ferric chloride used in coagulation/flocculation (35 – 100%, depending on impact category). Life cycle impact assessment showed that the lower the pollutant concentration, the higher the specific environmental impacts will be, which prompts for further detailed analysis of water treatment plant environmental performance in at least two directions: removal of emerging contaminants (present in very low concentrations) and a more detailed analysis on the individual performance of each treatment stage.

Keywords: drinking water, environmental impacts, life cycle assessment, operation

1. Introduction

Water resources are essential for humans and ecosystems, but due to problems such as climate change, industrialization, inadequate storage or insufficient wastewater treatment before discharge, qualitative improvements through water treatment processes are required to avoid human health risks and to provide sufficient and good water quality for drinking, industrial purposes and other economic activities by removing various contaminants (Prouty and Zhang, 2016; Garfí et al., 2016). Consequently, increasing efforts in terms of technology, chemical and energy inputs are required to meet water quality standards, thus increasing the environmental impacts and water production costs. The complex dynamics in water production sector require adequate performance evaluation of drinking water treatment plants (DWTP) to understand and quantify the environmental impacts that arise from water treatment processes and to find alternatives for costs minimization (WHO, 2011).

Life cycle assessment (LCA) has been used increasingly in the last decade as an instrument for environmental performance evaluation in the water sector because it provides a standardized platform to analyze treatment processes through an input-output approach and subsequently to identify and quantify associated environmental impacts (Lemos et al., 2013; Loubet et al., 2016b). This systemic approach to environmental analysis provides proven advantages such as: a high degree of objectivity, the realization of complex environmental profiles and the possibility to create and investigate scenarios related to the environmental performance of water production systems and facilities (Teodosiu et al., 2012; Mery et al., 2014). In the water sector, LCA has been used for applications like: evaluations in the whole water use cycle (Barjoveanu et al., 2014; Loubet et al., 2014), and for environmental performances assessment of water and wastewater treatment technologies (Corominas et al., 2013). A widely used approach is to use LCA to compare the environmental impacts of various water/wastewater treatment processes (usually advanced vs. conventional), technologies and development scenarios, multi-criteria assessment on issues like: costs (Capitanescu et al., 2016; Loubet et al., 2016a) and energy (Vakilifard et al., 2018). Besides comparison, LCA is also used to analyse other relevant aspects for water production like distribution systems (Sanjuan-Delmás et al., 2015; Piralta et al., 2012; Hajibabei et al., 2018), alternative sources (Godskesen et al., 2013; Lundie et al., 2004). Sometimes, LCA studies approach whole water services systems (Barjoveanu et al., 2014; Lemos et al., 2013; Zappone et al., 2014) and in these situations the analysis focuses on identifying, describing and comparing impacts of various stages in the water use cycle: water production, distribution, wastewater collection, wastewater treatment (Garfí et al., 2016; Loubet et al., 2016b).

In most cases, LCA studies considered the operational phase of water production stages, and only few considered the construction and decommissioning phases of water production facilities (Friedrich and Buckley, 2002; Igos et al., 2014). The most used functional unit is water production volume (usually 1 m^3) and most of these studies focus on process or technology performance from an environmental and sometimes economic point of view (e.g. (Barrios et al., 2008; Jeswani et al., 2015). In terms of environmental impacts, most LCA analyses identified electricity consumption and subsequent carbon emissions (Amores et al., 2013; Barjoveanu et al., 2014), and chemicals consumption (Lemos et al., 2013; Mery et al., 2014) as the most important impact generators in the water production sector. However, it should be noted that LCA studies on water treatment differ greatly at aspects such as: study planning, system limits, included/excluded processes, impact definitions and interpretation which make comparisons between these research efforts really difficult. With very few exceptions, the vast majority of LCA studies in this field focus their objectives on the main product, the treated water (hence the most usual functional unit of 1 m^3 of treated water) and do not necessarily consider other important parameters related to the operational performance of the water treatment plant, like raw water quality, contaminant removal efficiency etc.

In view of the aspects presented above, the objective of this study is to evaluate through LCA the environmental performance of Iasi DWTP. Iasi City is the most developed urban centre in the North-Eastern Romania with a population in its metropolitan area of more than 475,000 inhabitants. Besides its aim of identifying and quantifying Iasi DWTP's environmental impacts, this study brings an original perspective in LCA studies on water treatment plants by defining a new functional unit (FU). Our approach is focused especially on the operational performance of the plant and considers raw water quality in the FU definition. This perspective is investigated by testing two new indicators (kg of suspended solids removed / year and kg of organic matter expresses as TOC removed / year) against the traditional FU (1 m^3 of treated water).

2. Methodology

2.1. Iasi drinking water treatment plant

Iasi city has a complex water services system which comprises two water sources: a groundwater source in Timisesti, which is about 120 km away and a newer one which uses surface water from the River Prut (through Chirita Lake). Iasi DWTP has a treatment capacity between 0.6 and 1.15 m^3/s, which corresponds to a treated water output ranging from 2,150 up to 4,100 m^3/h, which is subsequently distributed to a population of approximately 105,000 people. The treated water in this plant meets the quality standards imposed by the European Council Drinking Water

Directive 98/83/EC ((EC, 1998)). In Table 1 a selection of water quality data and water flows is presented for 2015, the year for which this study was carried out. One may notice the high variability of raw water quality from Prut river, due mainly to its largest drainage basin from Eastern Romania.

Table 1. Physical-chemical properties of raw and treated water at Iasi DWTP in 2015

No	***Indicator***	***Unit***	***Average value***	***Max value***	***Min value***	***Average value***	***Max. value***	***Min. value***
			RAW WATER			**TREATED WATER**		
1	Water volume (total 2015)	m^3	13,551,832			13,365,175		
2	Water volume	m^3 / month	1,129,319	1,484,110	896,747	1,113,765	1,482,363	895,088
3	Turbidity	NTU	7.35	43.4	1.7	0.21	0.3	0.2
4	pH	U pH	8.26	8.4	8.1	7.73	7.9	7.5
5	Conductivity	μS/cm	636.88	705.0	492.5	648.75	717.5	510.0
6	Solid Residue	mg/L	293.25	399.5	30.0	311.68	388.0	143.5
7	Total suspended solids	mg/L	53.33	212.5	6.5	0.00	0.0	0.0
8	Alcalinity	ml HCl 0,1N	3.40	4.0	2.8	3.20	3.8	2.6
9	Total hardness	˚Ge	10.24	12.8	7.8	9.98	12.8	7.3
10	Temporary hardness	˚Ge	10.16	11.2	8.4	9.50	10.6	5.9
11	Permanent Hardness	˚Ge	1.40	1.9	0.9	1.96	2.5	1.2
12	Bicarbonates	mg/L	210.80	277.9	169.1	198.32	261.7	158.6
13	Chloride	mg/L	37.02	39.5	35.0	43.59	45.5	40.0
14	Oxidability	mg/L $KMnO_4$	11.86	12.9	7.3	8.33	9.4	7.1
15	TOC	mg/L	9.17	14.0	5.4	5.92	8.7	2.6
16	Calcium	mg/L	52.87	64.8	42.5	51.30	67.5	39.3
17	Magnesium	mg/L	17.18	19.9	13.6	17.00	19.9	12.6
18	Sulphates	mg/L	148.53	637.8	60.4	92.92	141.5	50.5
19	Nitrates	mg/L	2.59	4.4	1.3	2.45	3.9	1.3
20	Nitrites	mg/L	0.24	2.7	0.0	0.21	2.4	0.0
21	Ammonia	mg/L	0.10	0.4	0.0	0.01	0.0	0.0

The drinking water treatment process involves the following stages (see Fig. 1): pre-oxidation (with chlorine dioxide), pH-adjustment (with HCl), coagulation/flocculation with ferric chloride (or polyacrylamide and powdered activated carbon), followed by sedimentation, pH correction with calcium hydroxide, rapid sand filtration, granular activated carbon filtration (GAC) and final disinfection with chlorine gas.

2.2. *LCA methodology*

Life cycle assessment is a structured and standardized method, which quantifies all "inputs" as the consumed resources and "outputs" as released emissions and wastes, respectively. It furthermore describes and quantifies impacts against the environment and human health as well as resource depletion associated with the entire life cycle of any services or products (ISO 14040, 2006). Through LCA, the entire drinking water system can be analysed in order to obtain a complex profile of environmental impacts which can be evaluated in various impact categories.

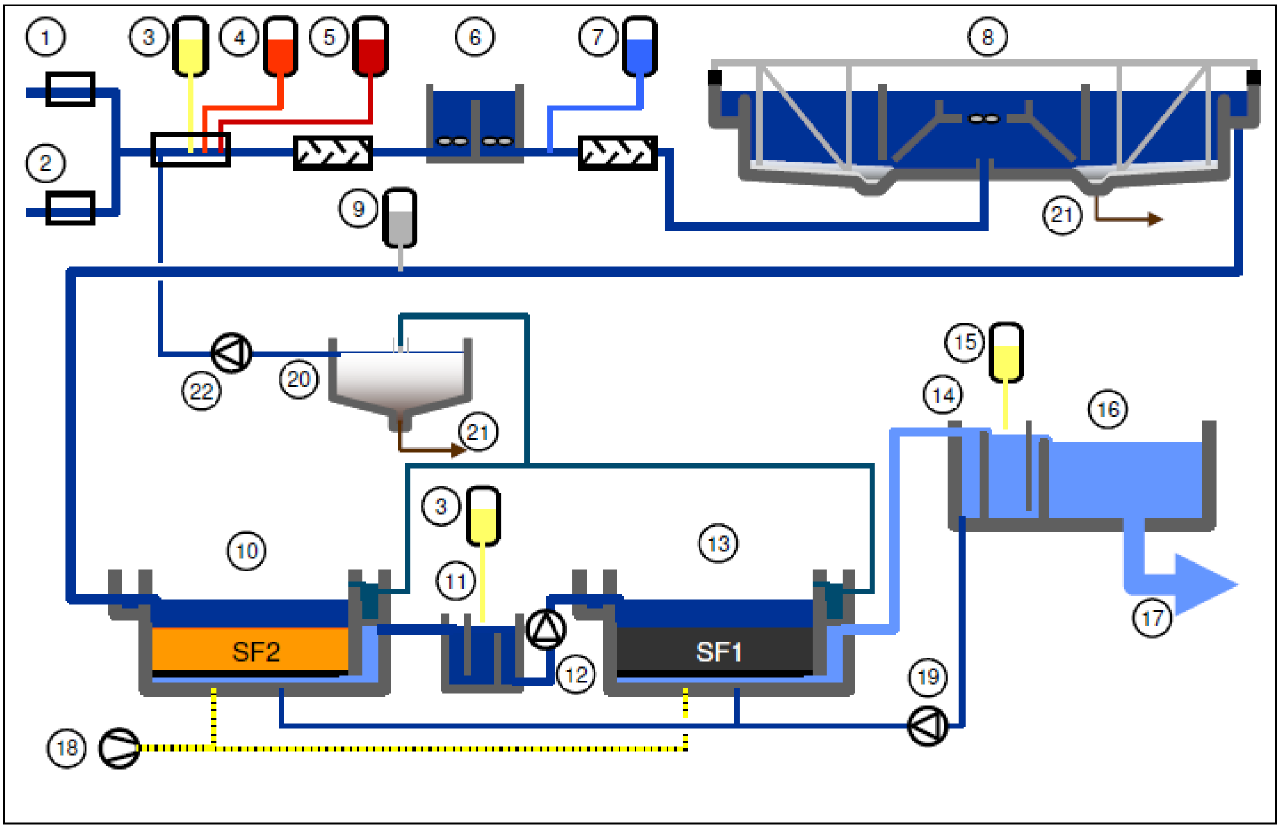
According to the ISO standards, an LCA consists of four phases as: Goal and scope definition; Life cycle inventory analysis (LCI); Life cycle impact assessment (LCIA) and Interpretation of results (ISO 14040, 2006). This structure of activities has been used in this study and is presented below.

2.3. System boundaries and functional units

The functional unit represents a quantitative measure of object submitted to a life cycle assessment and it is defined in relation to the object's function, hence its name. Traditionally, most of the studies concerning water-related systems (Barjoveanu et al., 2014; Ortíz Rodriguez et al., 2016) define their functional unit as a volume of water (treated, distributed, collected etc.) in combination with the system limits and the study objectives, as this approach defines exactly the product itself (water) and enables comparison of various processes or life cycle stages. It furthermore facilitates the analysis of water treatment plant environmental performance compared to its output. In this study, one cubic meter of treated water was considered as the reference case functional unit. Another option for functional unit could have been the "*volume per capita*" of population served, but this could not be implemented in our case due to data inconsistencies related to the complexity of Iasi water system.

Beside one cubic meter of delivered water, we approached the functional unit definition from a new perspective, which focused specifically on the environmental performance of Iasi DWTP. Because the purpose of any plant is to remove contaminants from raw water, it is useful to define a functional unit related directly to this objective, such as a unit of removed contaminant. Thus, our analysis also considers two other functional units that try to link plant operation to its environmental impacts: 1 kg of suspended solids removed and 1 kg of organic matter (expressed as TOC) removed from the raw water. This approach has been tested only in a few studies. Amini et al (2015) considered the importance of water quality in the functional unit definition (total yearly water volume treated to a certain quality). Bonton et al (2012) also mentioned this issue and considered 4 usual quality indicators in the definition of the functional unit (1 m^3 treated water), but did not mention how exactly this was performed.

In our study, the system limits included the processes presented in Fig. 1 and do not account for the pumping of raw water from Prut river or Chirita lake to the DWTP, and of treated water in the distribution system, although the pumping stations are located in the same area of the treatment plant.



1 Valve chamber Prut river
2 Valve chamber Chirita lake
3 Pre - oxidation agent dosing (using ClO_2)
4 Acid dosing (HCl)
5 Flocculant ($FeCl_3$)
6 Reaction Tank
7 Polyelectrolyte dosing
8 Clarifiers (2 individual units)
9 pH adjustment [using $Ca(OH)_2$]
10 8 sand filters (SF2)
11 Filtered water reservoir
12 Filtered water pumping station
13 8 GAC filters (SF1)
14 Backwash water reservoir
15 Disinfection (Cl_2)
16 Treated water reservoir
17 to existing pumping station
18 Air blowers station
19 Backwash water pumps
20 Recycle backwash water buffer tank
21 Sludge disposal into sewer
22 Recycle backwash water pumping station

Fig. 1. Iasi DWTP process flow

This study considers the construction and operational phases of Iasi DWTP life cycle, while the decommissioning phase is excluded due to lack of data. Most of the life cycle assessment studies of various water systems usually focus on the operational phase and only few references involved the construction of water treatment plants (Bonton et al., 2012; Igos et al., 2014).

2.4. Life cycle inventory & data collection

The life cycle inventory considers two phases of Iasi DWTP:

- The construction phase, which includes: land occupation, building materials relativized to the functional unit by considering a service life of 40 years for the whole treatment plant;

- The operational phase considers the material and energy inputs and waste outputs. Also, the transport processes of materials and chemicals used for in the operational phase are included in the inventory. These were calculated considering the location of each material supplier.

Table 2. Iasi DWTP inventory data

No	*Inventory input / Ecoinvent process*	*Unit*	*Comments*	*Data sources*	*Total*	*/ m^3 treated*	*/ kg TOC removed*	*/ kg SS removed*
Construction								
1	Land occupation / Occupation, heterogeneous, agricultural	m^2		Measured	51780.74	9.685E-05	0.0290	0.0019
2	Concrete / Concrete, normal {RoW}| unreinforced concrete production,| Alloc Def, U	m^3	40 years operation	Estimated based on buildings dimensions	69.38	5.190E-06	0.0015	0.0001
3	Steel Rebar / Steel rebar, production mix, at plant GLO S	kg	40 years operation	Estimated, considers 150 kg rebar / 1 m^3 concrete	9019.2	6.748E-04	0.2024	0.0133
Operation 2015								
1	Ferric chloride / Iron (III) chloride, 40% in H2O, at plant/CH U	kg	40% solution	Measured	340,850	0.0255	7.652	0.5044
2	Chlorine gas / Chlorine, gaseous, membrane cell, at plant/RER U	kg		Measured	24822	0.0018	0.5572	0.0367
3	Sodium chlorite / Sodium hypochlorite, 15% in H2O, at plant/RER U	kg	C=22.5 %d=1.2g/cm^3	Measured, modeled as sodium hypochlorite	47262	0.0035	1.0610	0.0699
4	Polyelectrolyte (polyacryl amide)/ Polyacrylamide {GLO}| production | Alloc Rec, U	kg	Polyacril amide	Measured	256	1.915E05	0.0057	0.0003
5	Quartz sand / Sand 0/2, wet and dry quarry, production mix, at plant, undried, EU-27 S System	kg	Quartz cristals (<0.8 mm), 20 years service life	Measured	17280	0.0013	0.3879	0.0255

No	Inventory input / Ecoinvent process	Unit	Comments	Data sources	Total	/ m^3 treated	/ kg TOC removed	/ kg SS removed
	- Copied from ELCD							
	Activated carbon / Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Alloc Def, U	kg	Granular activated carbon, 10 years service life	Measured	4800	0.00036	0.1077	0.0071
6	Natural gas / Natural gas, high pressure {Europe without Switzerland}| market group for | Alloc Def, U	m^3		Measured	6757	0.00050	0.1517	0.0100
7	Electricity / Electricity, high voltage {RO}| production mix | Alloc Rec, U	kWh		Measured	796955	0.0596	17.892	1.179
8	Transport / Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Alloc Rec, U	tkm	Sum of all transport processes (1417 km in total)	Calculated	71128.12	0.005322	0.10527	1.596

The inventory entries presented in Table 2 were modeled with the support of SimaPro software considering predefined unit processes sourced from Ecoinvent 3.3. data base.

2.5. Life cycle impact assessment

Life cycle impact assessment was performed with Recipe 1.13 midpoint method, which considers the impact categories presented in Table 3, together with their corresponding normalization values. The ReCiPe 1.13 method was favoured compared to other LCIA methods because it includes characterization factors for more pollutant species and some of its impact characterization models are updated as compared to older LCIA models.

Table 3. ReCiPe 1.13. Midpoint impact categories

No	Impact Category	Symbol	Unit	Normalization values (European set)
1	Climate change	CC	kg CO_2 eq	0.0000892
2	Ozone depletion	OD	kg CFC-11 eq	45.4
3	Terrestrial acidification	TA	kg SO_2 eq	0.0291
4	Freshwater eutrophication	FE	kg P eq	2.41
5	Marine eutrophication	ME	kg N eq	0.0988
6	Human toxicity	HT	kg 1,4-DB eq	0.00159
7	Photochemical oxidant formation	POF	kg NMVOC	0.0176
8	Particulate matter formation	PMF	kg PM_{10} eq	0.0671
9	Terrestrial ecotoxicity	Ttox	kg 1,4-DB eq	0.121
10	Freshwater ecotoxicity	Ftox	kg 1,4-DB eq	0.091
11	Marine ecotoxicity	Mtox	kg 1,4-DB eq	0.115
12	Ionising radiation	IR	kBq U235 eq	0.00016
13	Agricultural land occupation	ALO	m^2a	0.000221
14	Urban land occupation	ULO	m^2a	0.00246
15	Natural land transformation	NLT	m^2	6.19
16	Water depletion	WD	m^3	0
17	Metal depletion	MD	kg Fe eq	0.0014
18	Fossil depletion	FD	kg oil eq	0.000643

3. Results and discussion

3.1. Iasi DWTP environmental profiles

The life cycle impact assessment of Iasi DWTP was performed using the ReCiPe 1.13 midpoint method, which enabled the generation of complex environmental profiles presented and discussed in this section. The general environmental profile was issued in the characterization step of life cycle impact assessment (Fig. 2) and it shows the impact of one cubic meter of treated water. This profile shows that the most important contributor to the plant's impact is electricity consumption, followed by chemical consumption, while the transport of chemicals, the construction and operational phases of the plant only account for minor contributions in all impact categories.

In order to compare impact values among impact categories a normalization step was performed by using the normalization factors presented in Table 3. The results presented in Fig. 3 show that the highest impacts appear in water quality-related categories (freshwater eutrophication, freshwater eco-toxicity, marine eco-toxicity) and human toxicity, the major contributor being the electricity consumption.

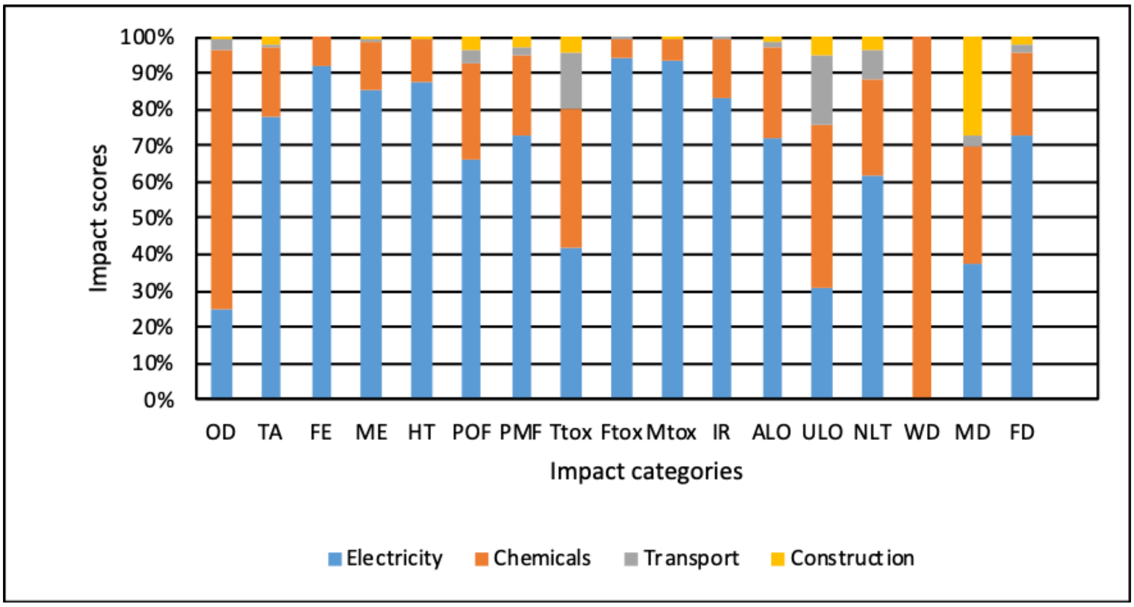


Fig. 2. General environmental impact of Iasi DWTP (characterization)

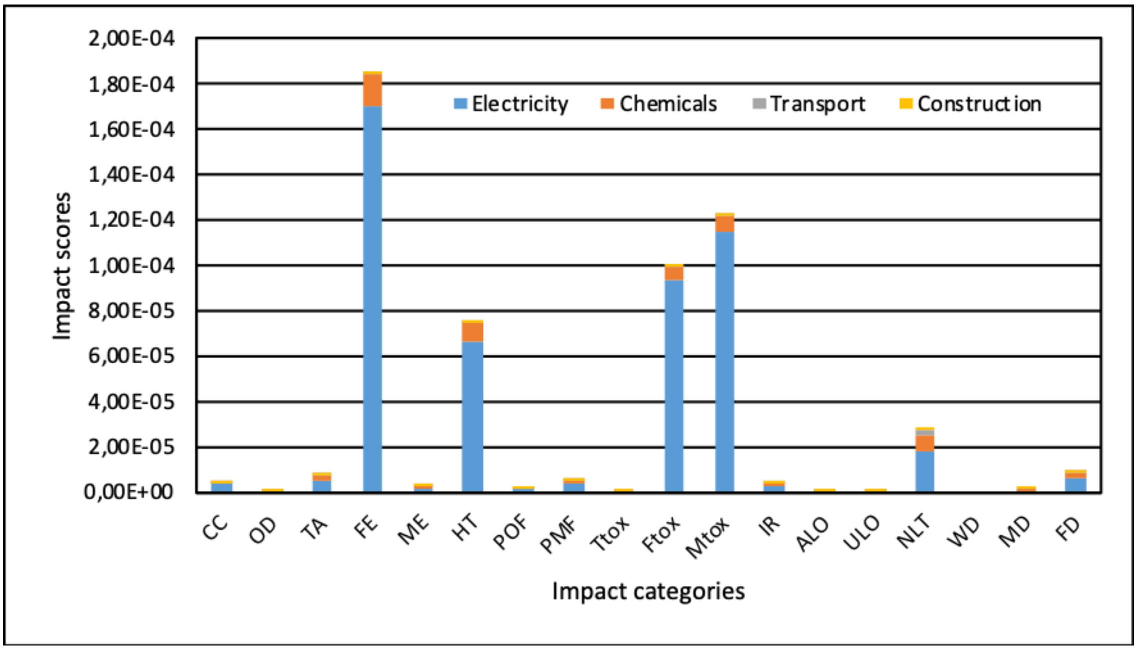


Fig. 3. General environmental impact profile (normalization)

These impact profiles are consistent with previous results obtained for the same treatment facility (Barjoveanu et al., 2014), albeit a different life cycle impact assessment method was used. Data in Fig. 2 and 3 show that Iasi DWTP environmental impact depends highly on its water productivity and specific electricity consumption. Related to this aspect, the structure of the electricity mix greatly affects Iasi DWTP environmental profile. In general, the environmental performance of this plant has the same structure and the same general contributors as other reports in literature (Ahmadi et al., 2016; Ortíz Rodriguez et al., 2016; Zappone et al., 2014), but a detailed comparison is virtually impossible due to major differences in systems definitions.

With respect to the construction phase, the general contribution in the total impact profile is insignificant. We may notice in Fig. 2 that construction only has a visible contribution in metal depletion category (about 30%, which is negligible in the normalized profile). Compared to other studies (Igos et al., 2014), in our case the construction phase has less impact, but this comparison is, again, too general as it is based on different systems data.

3.2. Operational plant performance assessment

As discussed above, a different approach was adopted in this work for the definition of the functional unit. So, rather than focusing on the end product of the DWTP, that is treated water, we have carried out a life cycle impact assessment considering the operational performance of Iasi DWTP and have defined two additional functional units considering the specific quantity of contaminants removed from raw water.

These functional units were defined and calculated for monthly quantities of total suspended solids and organic matter (expressed as TOC) respectively, considering the monthly average raw and treated water concentrations. It should be noted that this "average" approach does not capture all concentration variations of these contaminants, and thus the impacts presented in the next Figures may vary greatly.

In Fig. 4 and 5 the impact profiles of removing 1 kg of suspended solids and 1 kg of organic matter (expressed as TOC) are presented. The first observation is that the normalized impact structures are similar (also to the one presented in Fig. 3 for 1 m^3 treated water). This is caused by the functional units definition and by the way the inventory entries (Table 2) were computed using contaminants concentrations (considering that contaminants are dissolved in the same water volume). The impact values for various contributors to each impact category are different for the two functional units, but this stems from the different specific contributions of inventory entries relative to the functional unit, and it is not due to differences in inventory inputs, as the contaminants share the same water volume and go through the same treatment processes. This causes the similarity of the impact structure.

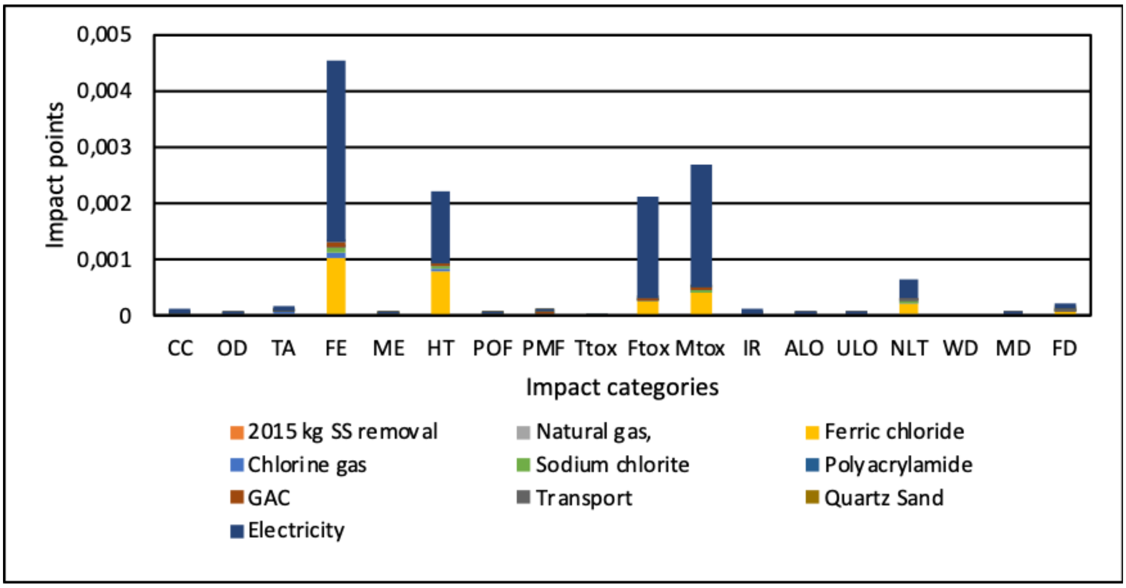


Fig. 4. Environmental impacts of removing 1 kg of suspended solids from raw water at Iasi DWTP in 2015

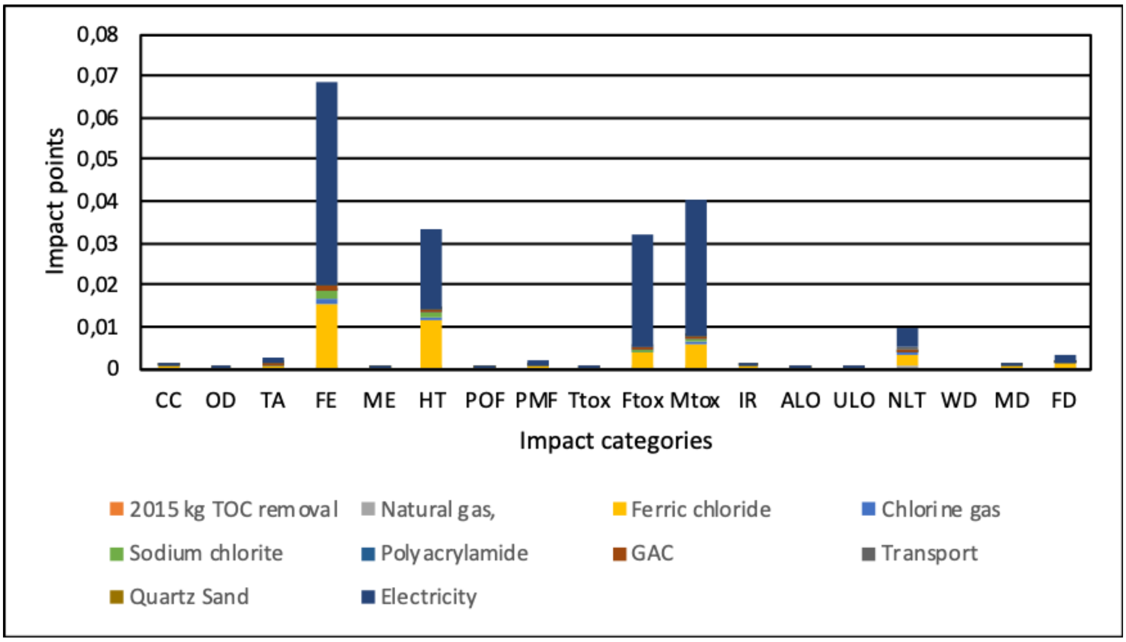


Fig. 5. Environmental impacts of removing 1 kg of organic matter (TOC) from raw water at Iasi DWTP in 2015

In the case of suspended solids removal (Fig. 4), beside electricity consumption (which mainly contributes to freshwater eutrophication, freshwater and marine eco-toxicity and to human toxicity categories), there is an important contribution of the coagulant use (in the same categories as electricity consumption contributes to). In the case of organic matter removal (TOC) (Fig. 5), the most important contributor is electricity, followed by ferric chloride consumption. This approach of investigating environmental impacts based on specific contaminant removal enabled the comparison of environmental performance at removing different contaminants, as presented in Fig. 6.

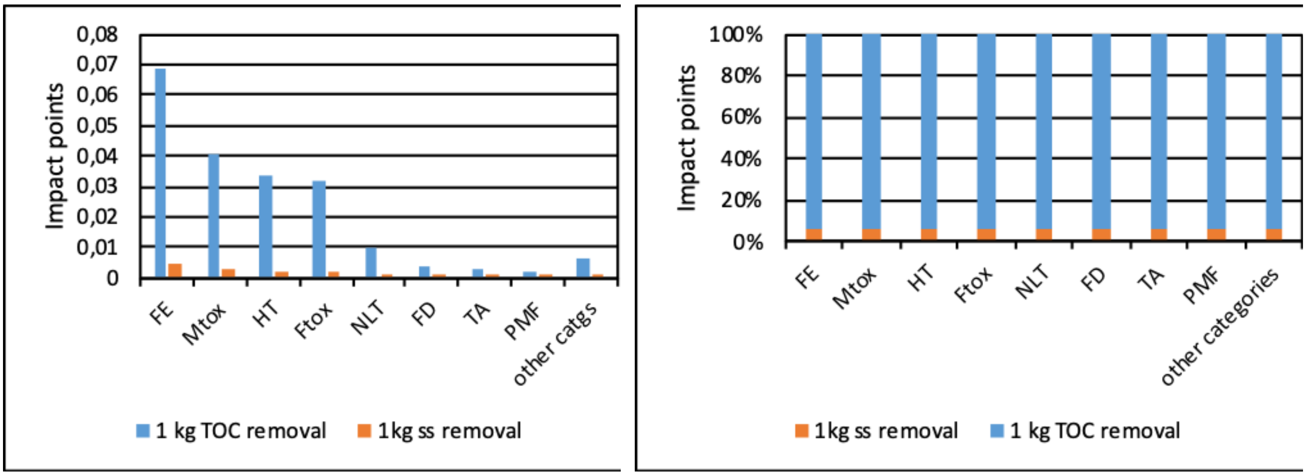


Fig. 6. Comparison of environmental performance for TOC and TSS removal (a. impact values and b. % of total impact per category)

Fig. 6 depicts the high differences in impact scores in various categories and it shows that the removal of organic matter (TOC) has impacts with an order of magnitude higher than the suspended solids removal . This may be explained if we remind that removed organic matter is much less than suspended solids (while both share the same water volume) and for removing one unit of TOC a higher volume of water needs to be processed.

Furthermore, it has to be noted that this comparison considers all treatment processes for all contaminants and it does not discriminate (at inventory level) which contaminant is removed in which treatment stage and also how much electricity or chemicals are consumed for the removal of a specific contaminant. Although this approach would have been (partially) possible for some inventory entries, and it would have generated more precise environmental profiles, it would have not been appropriate from an operational point of view because all water (which contains all contaminants) undergoes all operational treatment steps.

4. Conclusions

The life cycle assessment of Iasi DWTP was carried out considering its construction and operational phases and it showed that the operational phase generates considerably higher impacts than the construction one. The most important impact contributors are electricity consumption followed by chemicals consumption, which generates impacts in the water-related impact categories (eutrophication and eco-toxicity). These results are consistent with other studies.

This work showcased the possibility of defining different functional units for evaluating the environmental performance of drinking water treatment plants by considering the specific contaminant removal as a functional unit. Even with the limitation of performing the LCA analysis on average monthly data reported to the initial and final concentration values of the considered contaminants (involving high fluctuations of the deriving impacts), this study enabled to accurately calculate the environmental impacts generated when removing specific contaminants from raw water. Our study links the removal efficiency of the treatment plant for a given contaminant to its corresponding environmental impacts. The LCA analysis, furthermore shows that the lower the contaminant concentration, the higher the environmental impacts, which opens new research perspectives in using LCA to assess DWTP performance, with respect to emerging pollutants.

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