

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

Original

Environmental performance evaluation of a drinking water treatment plant: A life cycle assessment perspective / Barjoveanu, G., Teodosiu, C., Gilca, A.-F., Roman, I., Fiore, S.. - In: ENVIRONMENTAL ENGINEERING AND MANAGEMENT JOURNAL. - ISSN 1582-9596. - ELETTRONICO. - 18:2(2019), pp. 513-522. [10.30638/eemj.2019.048]

Availability:

This version is available at: 11583/2846385 since: 2020-09-22T14:11:27Z

Publisher:

Gheorghe Asachi Technical University of Iasi, Romania

Published

DOI:10.30638/eemj.2019.048

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

1 **ENVIRONMENTAL PERFORMANCE EVALUATION OF A DRINKING**
2 **WATER TREATMENT PLANT: A LIFE CYCLE ASSESSMENT**
3 **PERSPECTIVE**

4
5 **George Bârjoveanu¹, Carmen Teodosiu^{1*}, Andreea-Florina Gîlcă¹,**
6 **Ioana Roman^{1,2}, Silvia Fiore^{3*}**

7
8 ¹*Department of Environmental Engineering and Management, „Gheorghe Asachi” Technical*
9 *University of Iasi, 73 Prof. Dr. Doc. Dimitrie Mangeron Street, 700050 Iasi, Romania*

10 ²*SC Apavital SA Iasi, 10 M. Costachescu Street, 700495, Iasi, Romania*

11 ³*Department of Environment, Land and Infrastructures Engineering (DIATI), Politecnico di Torino,*
12 *Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

13
14 **Abstract**

15 Drinking water treatment aims to avoid or minimize some risks to human health and to provide
16 adequate water quality by removing physical, chemical and biological contaminants. However,
17 treatment processes require increasing efforts in terms of technology, chemicals and energy inputs,
18 which generate increased secondary environmental impacts and added water production costs. The
19 objective of this study is to evaluate the drinking water treatment plant (DWTP) in Iasi City
20 (Romania) by life cycle assessment (LCA) and to identify and characterize its environmental impacts.
21 Iasi DWTP involves the following scheme: pre-oxidation (chlorine dioxide), coagulation/flocculation,
22 sedimentation, pH correction (calcium hydroxide), rapid sand filtration, granular activated carbon
23 filtration and disinfection (chlorine gas). LCA was performed according to the ISO 14040 standard
24 with the support of SimaPro 8.3. software and Eco-invent 3.3 data base. Life cycle impact assessment
25 has been performed with Recipe 1.13. Midpoint method. The life cycle inventory included the
26 construction and operational phases. The novelty of this study was to define two additional
27 functional units related to removing contaminants besides the traditional 1 m³ of treated water. The
28 main contributors to impact in most categories were the electricity consumption (25 – 95%
29 depending on impact category) and the ferric chloride used in coagulation/flocculation (35 – 100%,
30 depending on impact category). Life cycle impact assessment showed that the lower the pollutant
31 concentration, the higher the specific environmental impacts will be, which prompts for further
32 detailed analysis of water treatment plant environmental performance in at least two directions:
33 removal of emerging contaminants (present in very low concentrations) and a more detailed
34 analysis on the individual performance of each treatment stage.

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

37

38 **1. Introduction**

39

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

50 Life cycle assessment (LCA) has been used increasingly in the last decade as an instrument
51 for environmental performance evaluation in the water sector because it provides a standardized
52 platform to analyze treatment processes through an input-output approach and subsequently to
53 identify and quantify associated environmental impacts (Lemos et al., 2013; Loubet et al., 2016b).
54 This systemic approach to environmental analysis provides proven advantages such as: a high
55 degree of objectivity, the realization of complex environmental profiles and the possibility to create
56 and investigate scenarios related to the environmental performance of water production systems and
57 facilities (Teodosiu et al., 2012; Mery et al., 2014). In the water sector, LCA has been used for
58 applications like: evaluations in the whole water use cycle (Barjoveanu et al., 2014; Loubet et al.,
59 2014), and for environmental performances assessment of water and wastewater treatment
60 technologies (Corominas et al., 2013). A widely used approach is to use LCA to compare the
61 environmental impacts of various water/wastewater treatment processes (usually advanced vs.
62 conventional), technologies and development scenarios, multi-criteria assessment on issues like:
63 costs (Capitanescu et al., 2016; Loubet et al., 2016a) and energy (Vakilifard et al., 2018). Besides
64 comparison, LCA is also used to analyse other relevant aspects for water production like
65 distribution systems (Sanjuan-Delmás et al., 2015; Piralta et al., 2012; Hajibabei et al., 2018),
66 alternative sources (Godskesen et al., 2013; Lundie et al., 2004). Sometimes, LCA studies approach
67 whole water services systems (Barjoveanu et al., 2014; Lemos et al., 2013; Zappone et al., 2014)
68 and in these situations the analysis focuses on identifying, describing and comparing impacts of
69 various stages in the water use cycle: water production, distribution, wastewater collection,
70 wastewater treatment (Garfí et al., 2016; Loubet et al., 2016b).

71 In most cases, LCA studies considered the operational phase of water production stages, and
72 only few considered the construction and decommissioning phases of water production facilities
73 (Friedrich and Buckley, 2002; Igos et al., 2014). The most used functional unit is water production
74 volume (usually 1 m³) and most of these studies focus on process or technology performance from
75 an environmental and sometimes economic point of view (e.g. (Barrios et al., 2008; Jeswani et al.,
76 2015). In terms of environmental impacts, most LCA analyses identified electricity consumption
77 and subsequent carbon emissions (Amores et al., 2013; Barjoveanu et al., 2014), and chemicals
78 consumption (Lemos et al., 2013; Mery et al., 2014) as the most important impact generators in the
79 water production sector. However, it should be noted that LCA studies on water treatment differ
80 greatly at aspects such as: study planning, system limits, included/excluded processes, impact
81 definitions and interpretation which make comparisons between these research efforts really
82 difficult. With very few exceptions, the vast majority of LCA studies in this field focus their
83 objectives on the main product, the treated water (hence the most usual functional unit of 1 m³ of
84 treated water) and do not necessarily consider other important parameters related to the operational
85 performance of the water treatment plant, like raw water quality, contaminant removal efficiency
86 etc.

87 In view of the aspects presented above, the objective of this study is to evaluate through LCA
88 the environmental performance of Iasi DWTP. Iasi City is the most developed urban centre in the
89 North-Eastern Romania with a population in its metropolitan area of more than 475,000 inhabitants.
90 Besides its aim of identifying and quantifying Iasi DWTP's environmental impacts, this study brings
91 an original perspective in LCA studies on water treatment plants by defining a new functional unit
92 (FU). Our approach is focused especially on the operational performance of the plant and considers
93 raw water quality in the FU definition. This perspective is investigated by testing two new indicators
94 (kg of suspended solids removed / year and kg of organic matter expresses as TOC removed / year)
95 against the traditional FU (1 m³ of treated water).

96

97 **2. Methodology**

98

99 *2.1. Iasi drinking water treatment plant*

100 Iasi city has a complex water services system which comprises two water sources: a
101 groundwater source in Timisesti, which is about 120 km away and a newer one which uses surface
102 water from the River Prut (through Chirita Lake). Iasi DWTP has a treatment capacity between 0.6
103 and 1.15 m³/s, which corresponds to a treated water output ranging from 2,150 up to 4,100 m³/h,
104 which is subsequently distributed to a population of approximately 105,000 people. The treated
105 water in this plant meets the quality standards imposed by the European Council Drinking Water

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

110

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

<i>No</i>	<i>Indicator</i>	<i>Unit</i>	<i>Average value</i>	<i>Max value</i>	<i>Min value</i>	<i>Average value</i>	<i>Max. value</i>	<i>Min. value</i>
			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

112

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

118

119 2.2. *LCA methodology*

120 Life cycle assessment is a structured and standardized method, which quantifies all “inputs”
 121 as the consumed resources and “outputs” as released emissions and wastes, respectively. It
 122 furthermore describes and quantifies impacts against the environment and human health as well as

123 resource depletion associated with the entire life cycle of any services or products (ISO 14040,
124 2006). Through LCA, the entire drinking water system can be analysed in order to obtain a complex
125 profile of environmental impacts which can be evaluated in various impact categories.

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

130

131 2.3. *System boundaries and functional units*

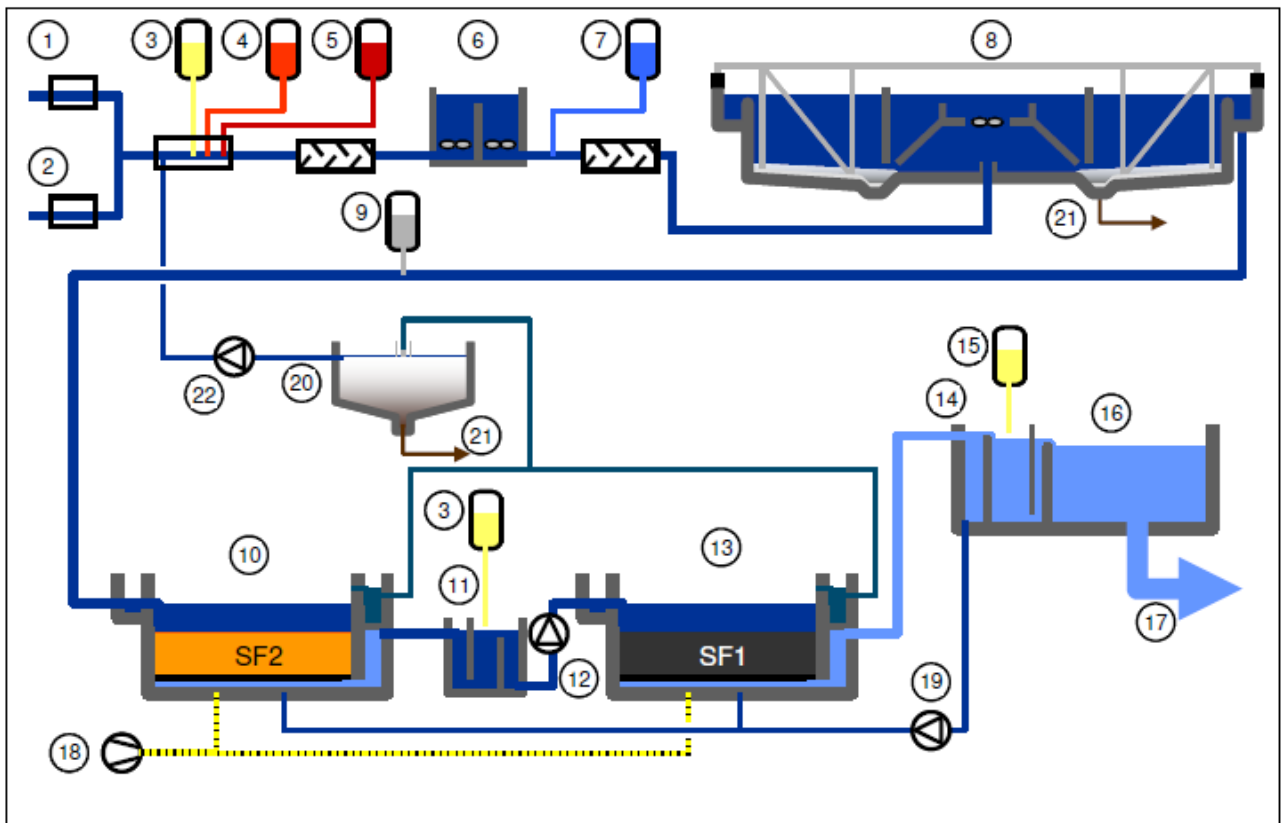
132

133 The functional unit represents a quantitative measure of object submitted to a life cycle
134 assessment and it is defined in relation to the object's function, hence its name. Traditionally, most
135 of the studies concerning water-related systems (Barjoveanu et al., 2014; Ortíz Rodríguez et al.,
136 2016) define their functional unit as a volume of water (treated, distributed, collected etc.) in
137 combination with the system limits and the study objectives, as this approach defines exactly the
138 product itself (water) and enables comparison of various processes or life cycle stages. It
139 furthermore facilitates the analysis of water treatment plant environmental performance compared
140 to its output. In this study, one cubic meter of treated water was considered as the reference case
141 functional unit. Another option for functional unit could have been the "*volume per capita*" of
142 population served, but this could not be implemented in our case due to data inconsistencies related
143 to the complexity of Iasi water system.

144 Beside one cubic meter of delivered water, we approached the functional unit definition
145 from a new perspective, which focused specifically on the environmental performance of Iasi
146 DWTP. Because the purpose of any plant is to remove contaminants from raw water, it is useful to
147 define a functional unit related directly to this objective, such as a unit of removed contaminant.
148 Thus, our analysis also considers two other functional units that try to link plant operation to its
149 environmental impacts: 1 kg of suspended solids removed and 1 kg of organic matter (expressed as
150 TOC) removed from the raw water. This approach has been tested only in a few studies. Amini et al
151 (2015) considered the importance of water quality in the functional unit definition (total yearly
152 water volume treated to a certain quality). Bonton et al (2012) also mentioned this issue and
153 considered 4 usual quality indicators in the definition of the functional unit (1 m³ treated water), but
154 did not mention how exactly this was performed.

155 In our study, the system limits included the processes presented in Fig. 1 and do not account
156 for the pumping of raw water from Prut river or Chirita lake to the DWTP, and of treated water in

157 the distribution system, although the pumping stations are located in the same area of the treatment
 158 plant.



- 159
- | | | |
|-----------------------------------|---|--|
| 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 $\text{Ca}(\text{OH})_2$] |
| 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 | |

160
 161
 162 **Fig. 1.** Iasi DWTP process flow
 163

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

168
 169 *2.4. Life cycle inventory & data collection*
 170

171 The life cycle inventory considers two phases of Iasi DWTP:

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

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

177
 178

Table 2. Iasi DWTP inventory data

<i>No</i>	<i>Inventory input / Ecoinvent process</i>	<i>Unit</i>	<i>Comments</i>	<i>Data sources</i>	<i>Total</i>	<i>/ m³ treated</i>	<i>/ kg TOC removed</i>	<i>/ kg SS removed</i>
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 H ₂ O, 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 H ₂ O, 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

<i>No</i>	<i>Inventory input / Ecoinvent process</i>	<i>Unit</i>	<i>Comments</i>	<i>Data sources</i>	<i>Total</i>	<i>/ m³ treated</i>	<i>/ kg TOC removed</i>	<i>/ kg SS removed</i>
	- 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

179

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

182

183 2.5. Life cycle impact assessment

184

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

190

191

192

193

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 ² a	0.000221
14	Urban land occupation	ULO	m ² a	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

195

196

197 3. Results and discussion

198

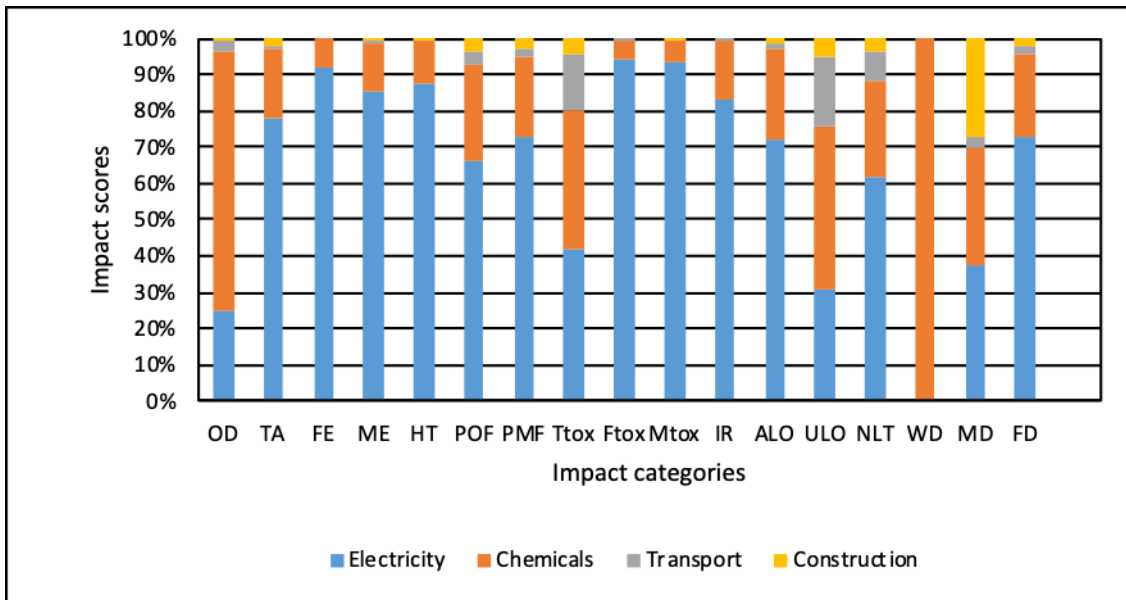
199 3.1. Iasi DWTP environmental profiles

200

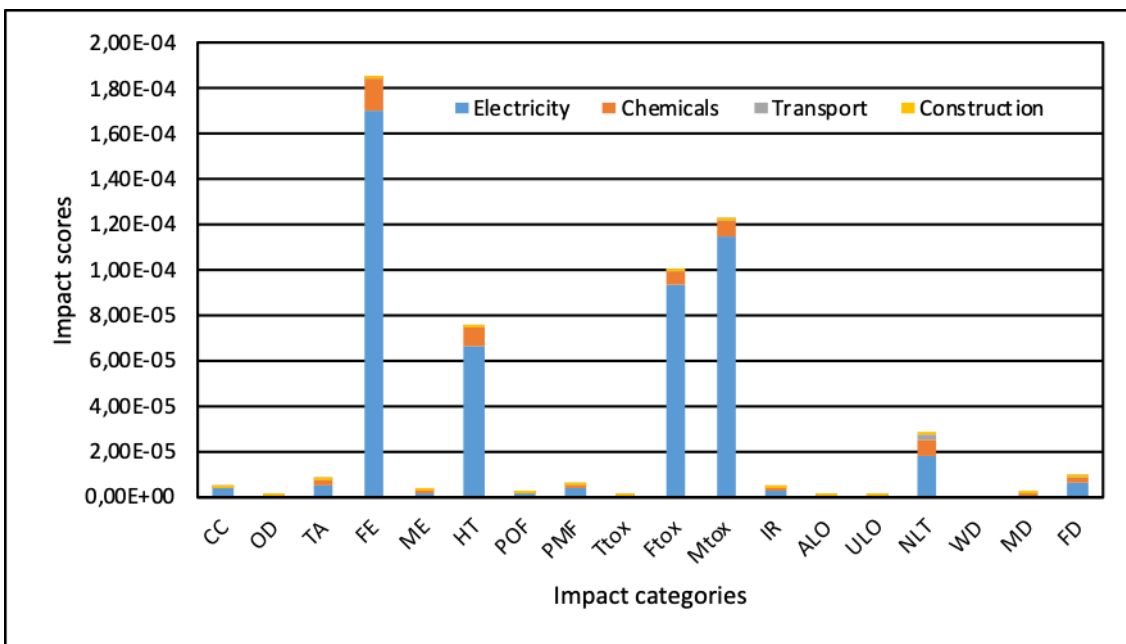
201 The life cycle impact assessment of Iasi DWTP was performed using the ReCiPe 1.13
 202 midpoint method, which enabled the generation of complex environmental profiles presented and
 203 discussed in this section. The general environmental profile was issued in the characterization step
 204 of life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

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

213



214
215
216 **Fig. 2.** General environmental impact of Iasi DWTP (characterization)
217



218
219
220 **Fig. 3.** General environmental impact profile (normalization)
221

222 These impact profiles are consistent with previous results obtained for the same treatment
223 facility (Barjoveanu et al., 2014), albeit a different life cycle impact assessment method was used.
224 Data in Fig. 2 and 3 show that Iasi DWTP environmental impact depends highly on its water
225 productivity and specific electricity consumption. Related to this aspect, the structure of the
226 electricity mix greatly affects Iasi DWTP environmental profile. In general, the environmental
227 performance of this plant has the same structure and the same general contributors as other reports

228 in literature (Ahmadi et al., 2016; Ortíz Rodríguez et al., 2016; Zappone et al., 2014), but a detailed
229 comparison is virtually impossible due to major differences in systems definitions.

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

235

236 3.2. *Operational plant performance assessment*

237

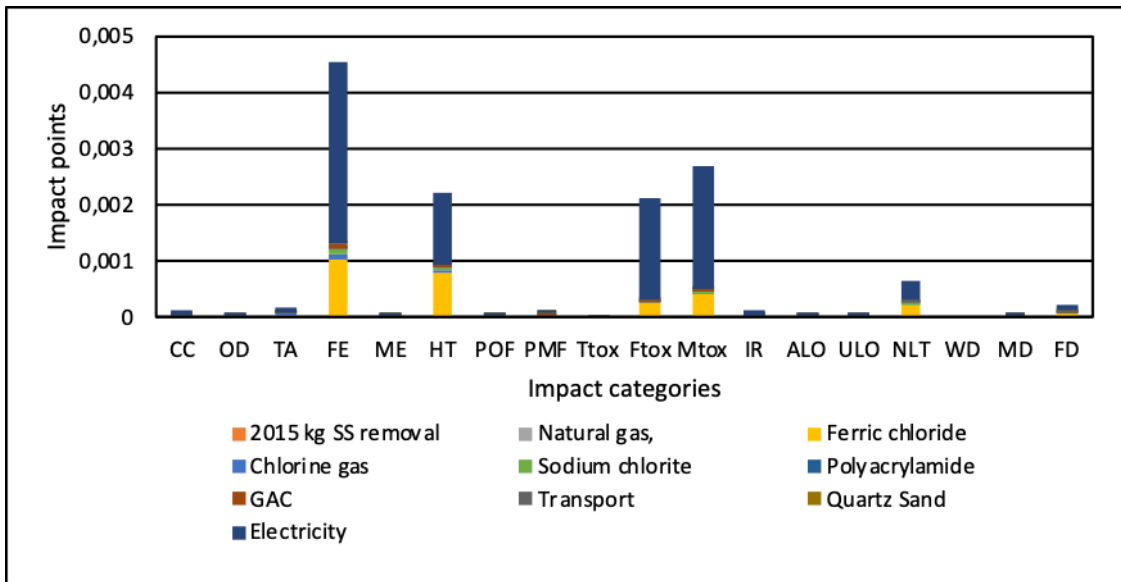
238 As discussed above, a different approach was adopted in this work for the definition of the
239 functional unit. So, rather than focusing on the end product of the DWTP, that is treated water, we
240 have carried out a life cycle impact assessment considering the operational performance of Iasi
241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

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

248 In Fig. 4 and 5 the impact profiles of removing 1 kg of suspended solids and 1 kg of organic
249 matter (expressed as TOC) are presented. The first observation is that the normalized impact
250 structures are similar (also to the one presented in Fig. 3 for 1 m³ treated water). This is caused by
251 the functional units definition and by the way the inventory entries (Table 2) were computed using
252 contaminants concentrations (considering that contaminants are dissolved in the same water
253 volume). The impact values for various contributors to each impact category are different for the
254 two functional units, but this stems from the different specific contributions of inventory entries
255 relative to the functional unit, and it is not due to differences in inventory inputs, as the
256 contaminants share the same water volume and go through the same treatment processes. This
257 causes the similarity of the impact structure.

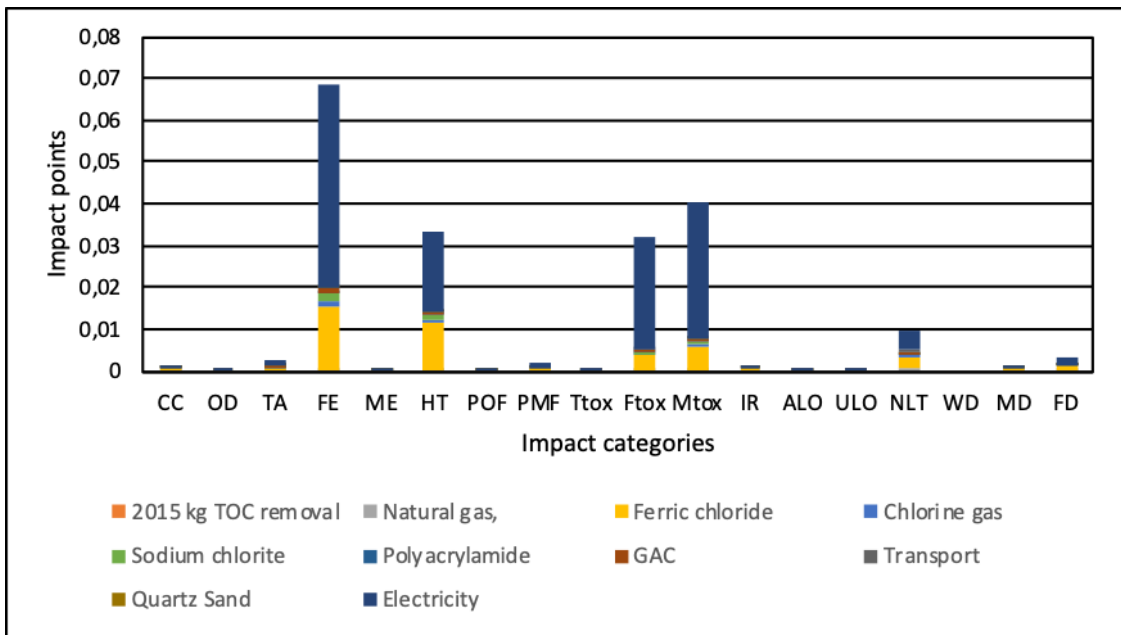
258

259



260
261
262
263
264

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



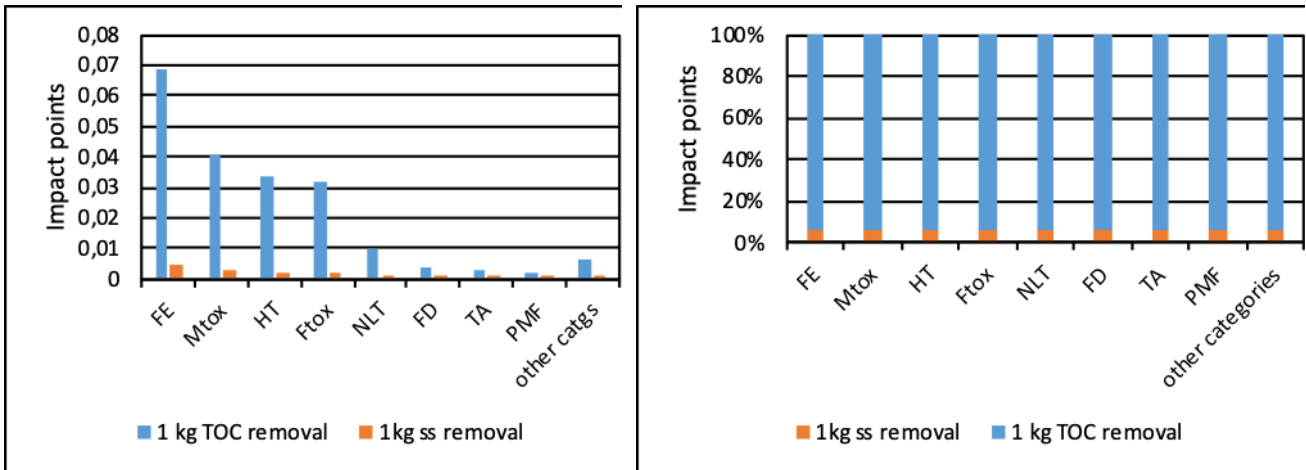
265
266
267
268
269

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

274 most important contributor is electricity, followed by ferric chloride consumption. This approach of
 275 investigating environmental impacts based on specific contaminant removal enabled the comparison
 276 of environmental performance at removing different contaminants, as presented in Fig. 6.

277
 278



279
 280 **Fig. 6.** Comparison of environmental performance for TOC and TSS removal (a. impact values and
 281 b. % of total impact per category)
 282

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

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

295

296 4. Conclusions

297

298 The life cycle assessment of Iasi DWTP was carried out considering its construction and
 299 operational phases and it showed that the operational phase generates considerably higher impacts

300 than the construction one. The most important impact contributors are electricity consumption
301 followed by chemicals consumption, which generates impacts in the water-related impact categories
302 (eutrophication and eco-toxicity). These results are consistent with other studies.

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

313

314 **Acknowledgement**

315 This work was supported by a grant of the Romanian Ministry of Research and Innovation, CCCDI-
316 UEFISCDI, project number 26PCCDI/01.03.2018, “*Integrated and sustainable processes for*
317 *environmental clean-up, wastewater reuse and waste valorization*” (SUSTENVPRO), within
318 PNCDI III.

319 The support of SC Apavital SA Iasi, the regional water operator is also acknowledged.

320

321 **References**

322

- 323 Ahmadi A., Tiruta-Barna L., Benetto E., Capitanescu F., Marvuglia A., (2016), On the importance
324 of integrating alternative renewable energy resources and their life cycle networks in the eco-
325 design of conventional drinking water plants, *Journal of Cleaner Production*, **135**, 872–883.
- 326 Amini A., Kim Y., Zhang J., Boyer T., Zhang Q., (2015), Environmental and economic
327 sustainability of ion exchange drinking water treatment for organics removal, *Journal of*
328 *Cleaner Production*, **104**, 413–421.
- 329 Barjoveanu G., Comandaru I.M., Rodriguez-Garcia G., Hospido A., Teodosiu C., (2014),
330 Evaluation of water services system through LCA. A case study for Iasi City, Romania. *The*
331 *International Journal of Life Cycle Assessment*, **19**, 449–462.
- 332 Barrios R., Siebel M., van der Helm A., Bosklopper K., Gijzen H., (2008), Environmental and
333 financial life cycle impact assessment of drinking water production at Waternet, *Journal of*
334 *Cleaner Production*, **16**, 471–476.

- 335 Bonton A., Bouchard C., Barbeau B., Jedrzejak S., (2012), Comparative life cycle assessment of
336 water treatment plants, *Desalination*, **284**, 42–54.
- 337 Capitanescu F., Rege S., Marvuglia A., Benetto E., Ahmadi A., Gutiérrez T.N., Tiruta-Barna L.,
338 (2016). Cost versus life cycle assessment-based environmental impact optimization of drinking
339 water production plants, *Journal of Environmental Management*, **177**, 278–287.
- 340 Corominas L., Foley J., Guest J.S., Hospido A., Larsen H.F., Morera S., Shaw A., (2013), Life
341 cycle assessment applied to wastewater treatment: State of the art, *Water Research*, **47**, 5480–
342 5492.
- 343 EC Directive, (1998). European Council Directive 98/83/EC of 3 November 1998 on the quality of
344 water intended for human consumption, *Official Journal of the European Union*, **L330**, 32–54,
345 On line at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31998L0083>.
- 346 Friedrich E., Buckley C., (2002) Life-cycle assessment as an environmental assessment tool in the
347 water industry, in: Paper Presented at the *Biennial Conference of the Water Institute of*
348 *Southern Africa* (WISA).
- 349 Godskesen B., Hauschild M., Rygaard M., Zambrano K., Albrechtsen H.J., (2013), Life-cycle and
350 freshwater withdrawal impact assessment of water supply technologies. *Water Research*, **47**,
351 2363–2374.
- 352 Igos E., Dalle A., Tiruta-Barna L., Benetto E., Baudin I., Mery Y., (2014), Life Cycle Assessment
353 of water treatment: What is the contribution of infrastructure and operation at unit process
354 level? *Journal of Cleaner Production*, **65**, 424–431.
- 355 Jeswani H.K., Gujba H., Brown N.W., Roberts E.P.L., Azapagic A., (2015), Removal of organic
356 compounds from water: Life cycle environmental impacts and economic costs of the Arvia
357 process compared to granulated activated carbon, *Journal of Cleaner Production*, **89**, 203–213.
- 358 Lemos D., Dias A.C., Gabarrell X., Arroja L., (2013), Environmental assessment of an urban water
359 system, *Journal of Cleaner Production*, **54**, 157–165.
- 360 Loubet P., Roux P., Bellon-Maurel V., (2016a), WaLA, a versatile model for the life cycle
361 assessment of urban water systems: Formalism and framework for a modular approach, *Water*
362 *Research*, **88**, 69–82.
- 363 Loubet P., Roux P., Loiseau E., Bellon-Maurel V., (2014), Life cycle assessments of urban water
364 systems: A comparative analysis of selected peer-reviewed literature, *Water Research*, **67**, 187–
365 202.
- 366 Lundie S., Peters G.M., Beavis P.C., (2004), Life Cycle Assessment for Sustainable Metropolitan
367 Water Systems Planning, *Environmental Science & Technology*. **38**, 3465–3473.
- 368 Ortíz Rodríguez O.O., Villamizar-Gallardo R.A., García R.G., Rodríguez O.O.O., Villamizar-
369 Gallardo R.A., García R.G., (2016), Life cycle assessment of four potable water treatment

370 plants in northeastern Colombia, *Ambiente e Agua - An Interdisciplinary Journal of Applied*
371 *Science*, **11**, 268.

372 Sanjuan-Delmás D., Petit-Boix A., Gasol C.M., Farreny R., Villalba G., Suarez-Ojeda M.E.,
373 Gabarrell X., Josa A., Rieradevall J., (2015), Environmental assessment of drinking water
374 transport and distribution network use phase for small to medium-sized municipalities in Spain.
375 *Journal of Cleaner Production*, **87**, 573–582.

376 Vakilifard N., Anda M., A Bahri P., Ho G., (2018), The role of water-energy nexus in optimising
377 water supply systems – Review of techniques and approaches, *Renewable & Sustainable*
378 *Energy Reviews*, **82**, 1424–1432.

379 Zappone M., Fiore S., Genon G., Venkatesh G., Brattebø H., Meucci L., (2014), Life cycle energy
380 and GHG emission within the turin metropolitan area urban water cycle. *Procedia Engineering*
381 **89**, 1382–1389.

382 Prouty, C. and Zhang, Q. (2016), How do people’s perceptions of water quality influence the life
383 cycle environmental impacts of drinking water in Uganda?, *Resources, Conservation and*
384 *Recycling*, 109, 24–33.

385 Garfí, M., Cadena E., Sanchez-Ramos, D., Ferrer-Marti, I., (2016), Life cycle assessment of
386 drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in
387 glass and plastic bottles, *Journal of Cleaner Production*, 137, 997–1003.

388 WHO (2011) World Health Organization: Guidelines for drinking-water quality - 4th ed. Available
389 at: http://www.who.int/water_sanitation_health/publications/2011/9789241548151_toc.pdf.

390 Loubet, P., Roux, P., Guérin-Schneider, L., Bellon-Maurel, V., (2016b) Life cycle assessment of
391 forecasting scenarios for urban water management: A first implementation of the WaLA model
392 on Paris suburban area, *Water Research*, 90, 128–140.

393 Teodosiu, C., Barjoveanu, G., Robu, B., Ene, S. A., (2012) Sustainability in the water use cycle:
394 challenges in the Romanian context, *Environmental Engineering and Management Journal*,
395 11(11), 1967–2000.

396 Mery, Y., Barna, L., Baudin, I., Benetto, E., Igos, E., (2014), Formalization of a technical procedure
397 for process ecodesign dedicated to drinking water treatment plants, *Journal of Cleaner*
398 *Production*, 68, 16–24. Amores, M. J. Meneses, M., Pasqualino, J., Antón, A., Castells, F.,
399 (2013) ‘Environmental assessment of urban water cycle on Mediterranean conditions by LCA
400 approach’, *Journal of Cleaner Production*, 43, 84–92.

401 Piralta, K. R., Ariaratnam, S.T., Cohen, A., (2012) Estimation of CO2 Emissions from the Life
402 Cycle of a Potable Water Pipeline Project, *Journal of Management in Engineering*, **28**(1), 22-
403 30;

- 404 Hajibabaei, M., Nazif, S., Tavanaei, F., (2018) Life Cycle Assessment of Pipes and Piping Process
405 in Drinking Water Distribution Networks to Reduce Environmental Impact, *Sustainable Cities
406 and Society*, **43**,
- 407 ILCD Handbook (2010) 'ILCD Handbook: General guide for Life Cycle Assessment -Detailed
408 guidance'. doi: 10.2788/38479.
- 409 ISO 14040 (2006) ISO 14040:2006(en) Environmental management — Life cycle assessment —
410 Principles and framework. Available at: [https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-
411 2:v1:en](https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en).
- 412 Bonton, A., Bouchard, C., Barbeau, B., Jedrzejak, S., (2012) Comparative life cycle assessment of
413 water treatment plants, *Desalination*, 284, 42–54.