LCA of wastewater treatment systems: Introducing a net environmental benefit approach

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Abstract
Life cycle assessment (LCA) allows evaluating the potential environmental impacts of a product or a service in relation with its function over its life cycle. In past LCAs applied to wastewater treatment plants (WWTP), the system function definition has received little attention despite its great importance. This has led to some limitations in LCA results interpretation. A new methodology to perform LCA on WWTP is proposed to avoid those limitations. It is based on net environmental benefit (NEB) evaluations and requires the assessment of the potential impact of releasing wastewater without and with treatment besides assessing the impact of the WWTP's life cycle. The NEB allows showing the environmental trade-offs between avoided impact due to wastewater treatment and generated impact by the WWTP's life cycle. The NEB is compared to a standard LCA through the case of a small municipal WWTP in the Province of Quebec, Canada. The WWTP consists of four facultative aerated lagoons in series. The NEB and standard LCA show similar results for impact categories solely related to the WWTP's life cycle but differ in categories where wastewater treatment environmental benefit is accounted for.
Keywords
Facultative aerated lagoons; greenhouse gas; life cycle assessment

INTRODUCTION

Life cycle assessment (LCA) is a method which allows assessing the environmental impact of a product or a service in relation with its function over its whole life cycle. The general LCA methodology is set by ISO 14040 standards (ISO 14040, 2006) dividing it in four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. The first step requires setting the function of the product or service under study. This function must be clearly defined considering that the whole environmental impact assessment is conducted in relation with the function and that it serves as a basis to settle two elements of prime importance for the assessment: the functional unit and the system boundaries.

Despite the impact of the function's definition on the interpretation of LCA results, little attention has been paid to it in the several LCAs related to wastewater treatment. In the rare LCAs conducted on wastewater treatment plant (WWTP) that tackled the function's definition, the main function of a WWTP was defined as the removal of pollutants present in water so that it reaches satisfactory values before release in natural water courses (Hospido et al., 2004; Gallego et al., 2008). However, this definition implies several limitations in the interpretation of LCA results because it neither takes into account the influent water quality nor the treatment efficiency, whereas these are two key criteria to assess the environmental performance of a WWTP. To compensate for these limitations, some LCAs indirectly included the influent quality by setting the functional unit in terms of person equivalent (p.e.) served by the WWTP (Tillman et al., 1998; Gallego et al., 2008) or more directly by defining some influent quality parameters (Foley et al., 2010).

Another limitation induced by the aforementioned function's definition comes from the fact that it leads to associate the environmental impact of the pollution entering the WWTP solely to this element of the urban water cycle even though it does not generate this pollution itself. This last remark is confirmed by the LCAs of Lundie et al. (2004) and Lassaux et al. (2008) which concluded that the WWTP contributes mainly to the global environmental load of the whole water system basically because of the residual load rejected in receiving water after treatment.

The aforementioned limitations and the conclusion of Vanrolleghem et al. (1996) regarding the fact that an integrated (holistic, overall) performance index would be a valuable tool for the design and operation of a WWTP have led us to develop a methodology based on the net environmental benefit concept to represent more explicitly the function of a WWTP and its overall environmental performance.

METHODOLOGY

NEB approach

Considering the fact that a WWTP is a priori considered as a treatment system which itself has environmental impacts associated with its life cycle (Hospido et al., 2004), we argue that tackling the main function of a WWTP requires assessing the net environmental benefit (NEB) linked to the WWTP. To do so, an integrated performance index is developed. This index requires considering the incoming wastewater as a starting point to ensure that the trade-off between the potential impact of rejecting untreated wastewater and the potential impact of rejecting treated wastewater and WWTP emissions is explicitly expressed. The estimation of the NEB of a WWTP that we are introducing combines the objective performance index (J) proposed by Vanrolleghem et al. (1996) with the NEB term used by Hellweg et al. (2005) to compare the cost-benefit and cost-effectiveness of municipal solid waste treatment. The index proposed by Vanrolleghem and al. (1996) is expressed by the following equation:

$$J = \text{Input} - \text{Output} + \text{Conversion} \tag{1}$$

Where all the terms of this equation are translated into corresponding cost and value expressing the sustainability of the system. The *Input* term is the (negative) value associated with the incoming wastewater, the *Output* term is the value of the effluent wastewater, and other emissions at the WWTP, and the *Conversion* term takes the investment and operation costs linked to the WWTP. The NEB indicator used by Hellweg et al. (2005) represents the net environmental benefit of implementing an end-of-pipe (EOP) treatment option compared to a null option. It is expressed as the impact potential (IP) difference between the null option and the EOP treatment option by equation 2 (for an LCA, the impacts are considered potential since they are mostly long term impacts that are determined from global models):

$$NEB = IP_{NO} - IP_{EOP} \tag{2}$$

The methodology that we are introducing for the evaluation of the NEB of a WWTP consists of using LCA to assess the potential impact (PI) with and without the WWTP through the following equation:

$$NEB = PI_{NO} - [PI_{TW} + PI_{SLC}] \tag{3}$$

Where the PI_{NO} term corresponds to the potential impact of rejecting wastewater without any treatment into the environment (null option), the PI_{TW} corresponds to the potential impact of rejecting the treated wastewater into the environment and the PI_{SLC} corresponds to the potential impact of the resources extracted and the emissions generated by the life cycle of the WWTP according to the system boundaries. The LCA methodology allows assessing NEB using life cycle impact assessment (LCIA) methods to evaluate an integrated performance index which can take into account most of major environmental problems.

Methods comparison

Compared to Hellweg et al. (2005), the NEB index that we propose separates the potential impact of the rejected treated wastewater from the potential impact of the WWTP's life cycle. This allows assessing the environmental benefit from the receiving water perspective through the difference between the first two terms of equation 3. One must also note that the expression *impact potential* (IP) used by Hellweg et al (2005) has the same meaning as the expression *potential impact* (PI) retained in this article, the latter being more commonly used. Vanrolleghem et al. (1996) proposed gathering the effluent wastewater and other WWTP emissions (ie: grit, gas, sludge) in the Output term of the performance index (J) but separating the WWTP operation intake in the Conversion term. We did not retain this approach because it is not allowing a direct estimation of the environmental benefit for the receiving water and so limits the estimation of the WWTP efficiency. In comparison with the NEB approach, a standard LCA of a WWTP would provide results as the sum of the last two PI terms of equation 3 only which leads associating the impact of incoming wastewater solely to the WWTP and does not allow assessing its environmental performance. In relation to the LCA field, the NEB approach can be seen as a comparative LCA where a null option scenario is compared with a treatment scenario. Globally the NEB approach is more data intensive than a standard LCA conducted on a WWTP because one must gather data related to influent quality whereas this is not necessary for a standard LCA. Also to avoid skewing the NEB assessment, it is important to track the same pollutants in the influent, effluent and during treatment. If this aspect is disregarded the potential impact generated by the incoming wastewater will be added only to the WWTP's life cycle without a positive environmental counterpart associated to its removal.

Case study presentation

The NEB approach is illustrated through the case study of a WWTP of a small city in the Province of Quebec, Canada. The treatment consists of four facultative aerated lagoons in series equipped with static aerators. The first three lagoons mainly aim at removing organic matter whereas the last one serves as a polishing pond. From May to November included, phosphorus removal is done by dosing aluminum sulphate at the inlet of the last lagoon. The lagoons have a total operating volume of 215,700 m^3, an operating height of 4.6m, occupy an area of 10 ha and serve 10,500 persons. Treated wastewater is rejected in an influent of the St-Lawrence River. The WWTP was designed considering that most of the organic and particular loads come from food industries and more than half of the design flow of 8750 m^3 comes from infiltration caused by the sewer being in a high level water table zone. From a LCA perspective, the boundaries of the system used to estimate the PI terms of the NEB approach are presented in figure 1.

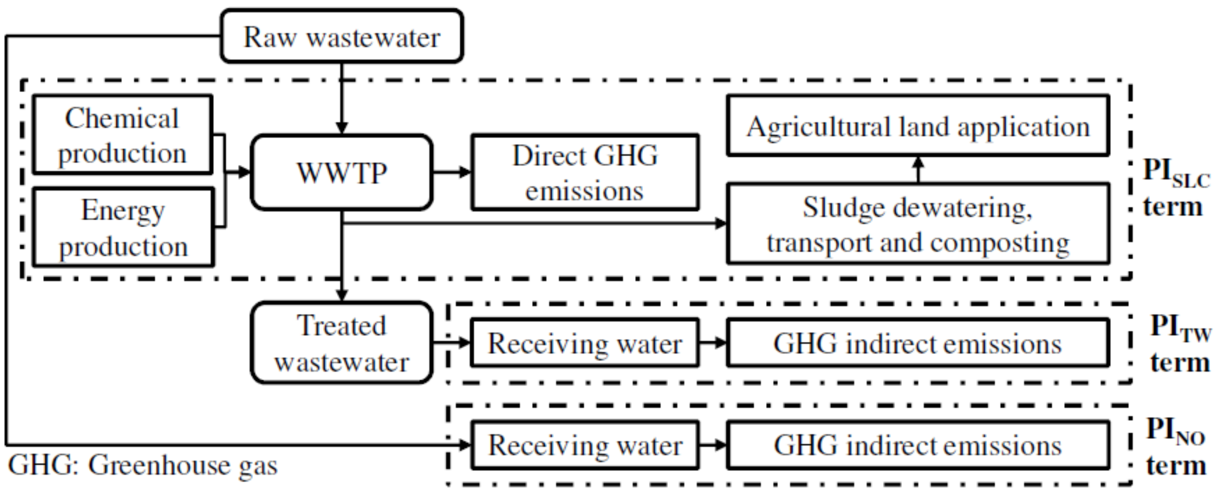

Figure 1. System description and boundaries of the NEB PI terms considered

As shown in figure 1, the case study is limited to the operational phase. This choice is based on previous LCAs performed on different WWTP types showing that the construction and decommissioning processes have very small contributions to the overall impact (Emmerson et al., 1995.; Renou et al., 2008). The functional unit has been set as 1 m^3 of raw wastewater entering the WWTP. The average load corresponding to 1 m^3 of raw wastewater is shown in table 1. The data come as much as possible from the 2007, 2008 and 2009 WWTP monitoring and sludge disposal reports. Values of table 1 were calculated per m^3 of raw wastewater considering the total load and treated wastewater volume during the 2007-2009 period during which the mean daily flow was 7873 m^3/d. Nutrient loads are estimated considering unit loads of 10 g TKN/pers./d, 5 g NH_4/pers./d and 2g Ptot/pers./d (Bernier, 2001).

WWTP operation and sludge production

Sludge produced by the treatment process was removed after a build-up period of approximately ten years (1995-2005). A short time before this removal, the sludge volume of each lagoon was estimated through several in-situ thickness measurements whereas sludge nutrient and heavy metal content were determined from sludge samples analysis. Based on these data, sludge heavy metal and fertilizing loads are estimated in relation to the functional unit by considering the volume of wastewater that had been treated over the sludge build-up period. These measured sludge nitrogen and phosphorus loads are considered in table 1 to estimate removal and effluent load by assessing mass balance over the system. In this way, the effluent nitrate was calculated from the influent estimated TKN and measured sludge TKN considering that this WWTP was designed to provide sufficient aeration for nitrification during summer. In table 2, the WWTP global energy input and chemical consumptions for phosphorus removal are presented along with the inventory data related to sludge disposal.

Table 1. Average load corresponding to 1 m^3 of raw wastewater

Parameter	Average load			Units	Data source
	Influent	Effluent	Sludge		
COD	480	57	-	g COD/m^3	Operation data from 2007, 2008 and 2009 WWTP monitoring reports
BOD_5	220	12	-	g BOD_5/m^3	
TSS	140	14	-	g TSS/m^3	
pH		7.4	-	-	
Ammonium (NH_4)	-	9	-	g $N\text{-}NH_4/m^3$	
	6.5	-	0.1	g $N\text{-}NH_4/m^3$	-Influent data estimated from unit load (Bernier 2001). -Effluent data estimated by mass balance. -Sludge disposal report.
Total Kjeldahl nitrogen (TKN)	13	9	0.4	g N/m^3	
Nitrate (NO_3^-)	-	3.5	-	g $N\text{-}NO_3^-/m^3$	
Total phosphorus (Ptot)	2.7	2.2	0.5	g P/m^3	

(a)Considered equal to the measured ammonium in the effluent (i.e. organic nitrogen concentration is considered negligible in the effluent)

Table 2. WWTP operation and sludge disposal inventory per m^3 of raw wastewater

Parameter	Value	Units
Energy and chemicals associated with the operation of the system		
Wastewater treatment total energy input	0.778	kWh/m^3
Aluminum sulphate for phosphorus removal	0.021	kg/m^3
Sludge dewatering, transport and composting		
Sludge production	0.19	kg/m^3
Sludge mean dryness	23	%
Sludge production (Dry Matter)	0.04	kg DM/m^3
Energy input for sludge dewatering	0.0005	L $diesel/m^3$
Transport distance to composting site	41	km
Electricity for ventilation	0.001	kWh/m^3
Mobile equipment diesel consumption	0.0003	L $diesel/m^3$

Regarding sludge disposal, it was dewatered on site and was transported to a composting facility. The compost was then transported to be spread on agricultural lands. The energy consumption for mechanical dewatering was estimated from information provided by the private contractor and the transport distance between the WWTP and the composting facility (41 km). As no actual data is available for the sludge composting process, the energy consumption related to this process was estimated from the data of Suh and Rousseaux (2002) including electricity for ventilation of 30 kWh/t Dry Matter (DM) and diesel oil for mobile equipment of 8.4 kg/tDM. Due to the uncertainty regarding the compost fertilizing effect (Renou et al., 2008), no substitution of mineral fertilizer was considered for agricultural land application, i.e. no fertilizing credit is attributed to the sludge. For the same reason, energy for transport and sludge spreading on agricultural land were also excluded from the analysis.

Heavy metals

Due to the importance of heavy metal effects in human toxicity and ecotoxicity as shown in previous LCAs (Hospido et al., 2004; Gallego et al., 2008), the potential impact of adding heavy metal to agricultural soil through sludge spreading is considered in this study. To avoid disregarding heavy metal potential impact, influent and effluent heavy metal data have been measured for the case study completing the data from sludge heavy metal content. This was done by analysis of a 24 hour composite sample of the influent and a grab sample of the effluent. Considering the important mixing due to aeration and the long retention of the lagoons the effluent grab sample is considered representative of daily mean effluent. Measured heavy metal concentrations and estimated sludge content for 1 m^3 of raw wastewater are presented in table 3 along with the metallic species that was considered for impact assessment. This table also shows the aluminum sludge content due to chemical phosphorus removal.

Table 3. Heavy metals content of sludge, influent, effluent and chemical forms considered

Parameter	Heavy metals loads			Chemical species considered for impact assessment	
	Influent	Effluent	Sludge		
	mg/m^3			Sludge	Wastewater
Aluminum (Al)	-[(a)]	-[(a)]	620	-	-
Arsenic (As)	3.7	3.3	0.3	As	As^{5+}
Chromium (Cr)	2.8	<0.5 [(b)]	2	Cr^{3+}	Cr^{6+}
Cobalt (Co)	1.1	0.7	0.3	Co	Co
Copper (Cu)	29	3	8	Cu^{+}	Cu^{+}
Mercury (Hg)	0.3	<0.2 [(b)]	0.1	Hg	Hg
Nickel (Ni)	4	<1 [(b)]	1.3	Ni	Ni^{2+}
Lead (Pb)	3	<1[(b)]	2	Pb	Pb

(a) *Unmeasured parameter*
(b) *Below detection limit*

With respect to the life cycle impact assessment (LCIA), when heavy metal concentrations were below the detection limits, the detection limits themselves were used to estimate the maximum potential toxicity impact of the wastewater. In table 3, chemical species considered for impact assessment were chosen to ensure impact factors would be associated to each measured heavy metal by the LCIA method retained. Since the retained LCIA method does not include any impact factor for aluminum, no chemical species were considered for aluminum. In table 3, chemical species for chromium are based on the study of Doka (2009). One must note that the measured concentrations of heavy metals in wastewater are based on grab sample measurements made in January 2011 whereas sludge concentrations were estimated from long term mass balances (1995-2005). However, the differences between measured influent and effluent concentrations of heavy metals are of the same order of magnitude as those estimated from the sludge. Considering the uncertainty of LCIA regarding toxicity impact categories (Renou et al., 2007), this level of precision in the estimation of heavy metal concentrations seems suitable for the case study.

Greenhouse gas emissions

As shown in figure 1, the direct GHG emissions from the treatment process and the indirect GHG emissions generated in the receiving water bodies due to the rejection of treated or non-treated wastewater have been included in the case study. The indirect GHG emissions are particularly important when large COD loads are emitted in the receiving waters causing potential methane emissions induced by methanogenic conditions (Foley and al., 2010), e.g. for the null option case. Mid-range value emission factors from the IPCC Guidelines (IPCC, 2006) have been used to assess the CH_4 and N_2O emission potentials. Regarding the COD emissions, the fraction of COD that is anaerobically degraded into CH_4 was removed from the total COD load to avoid double counting of its impact. Table 4 shows the GHG emission factors considered and corresponding GHG emissions per m^3 of raw wastewater. The global warming potential expressed in CO_2 equivalent are also shown in table 4. The GWP is assessed using GWP factors for a time scale of 100 years (GWP100) of 20 kg CO_2 eq./kg biogenic CH_4 and 296 kg CO_2 eq./kg N_2O. These GWP100 factors were taken from the LCIA method used for the case study and are discussed in the following section.

Table 4. Direct and indirect GHG emissions factor and emissions per m^3 of raw wastewater

Parameter	Emission Factor		GHG emission		GWP100
	Units	Value	Units	Value	(g CO_2 eq/m^3)
CH_4 from effluent discharge to receiving water without treatment	kg CH_4 per kg COD discharged	0.025	g CH_4/m^3	12	240
CH_4 from effluent discharge to receiving water with treatment			g CH_4/m^3	1	29
CH_4 from WWTP operation	kg CH_4 per kg COD removed	0.0125	g CH_4/m^3	5.3	106
N_2O from effluent discharge to receiving water without treatment	kg N_2O-N per kg N discharged	0.0025	g N_2O/m^3	0.05	16
N_2O from effluent discharge to receiving water with treatment			g N_2O/m^3	0.04	10
N_2O from WWTP operation	g N_2O/pers./yr.	3.2	g N_2O/m^3	0.01	3

Impact assessment

The inventory and impact assessment phases were performed with the SimaPro 7.2 LCA software. Our inventory was completed using the Ecoinvent database Version 2.2 for secondary processes like transport and primary resource production for aluminum sulphate. The Quebec electricity mix where 95% of the electricity is generated from hydropower was also added to the database to assess the electricity input potential impact. The LCIA method CML 2 baseline 2000 Version 2.05 was retained for impact assessment since it has already been compared to five widely used LCIA methods to show the influence of the impact assessment method in wastewater treatment LCA (Renou et al., 2007). Renou et al. (2007) obtained similar results between these five methods for greenhouse effect, resources depletion, acidification and eutrophication but large discrepancies appeared for human toxicity. Based on this study, CML 2 baseline 2000 appears to be the most appropriate method in our case since it globally maximises the water pollutant parameters that are taken into account in the impact assessment. However, this method does not include any impact factor for aluminum which is present in high quantity in the sludge (table 3). This issue will be addressed in future research. Also, a problem-oriented (midpoint) approach like CML 2 baseline 2000 is more suitable to track the trade-off between impacts generated by the WWTP's life cycle and the environmental gain related to wastewater pollutant removal than more aggregated damage oriented (endpoint) methods.

RESULTS AND DISCUSSION

Results of the LCIA according to the NEB methodology are summarized in table 5 which also presents the results that a standard LCA would provide. Globally the NEB shows a trade-off between impact generated by the WWTP's life cycle expressed as negative NEB and avoided impacts thanks to rejected wastewater quality improvement expressed as positive NEB values. More precisely, the positive NEB value for eutrophication is due to organic matter and nutrient removal. Its counterpart corresponds to the negative NEB values for ozone layer depletion, acidification and abiotic depletion mainly caused by electricity consumption for aeration and production of aluminum sulphate for phosphorus removal. Concerning toxicity categories, the NEB approach allows seeing the trade-off between positive NEB for marine and freshwater aquatic ecotoxicity from heavy metals removal which are transferred to human and terrestrial ecotoxicity impact categories through agricultural land spreading of the produced sludge. The positive NEB associated to global warming and photochemical oxidation comes from the electricity mix containing low fossil fuel primary energy sources in the Province of Quebec, Canada. The positive NEB values for these categories are mainly due to the removal of COD which limits the indirect

CH_4 emission in receiving water. This last remark is confirmed by the GWP100 values reported in table 4.

Table 5. LCIA results expressed as NEB and standard LCA

Impact categories CML 2 baseline 2000	Units	PI_{NO}	PI_{TW}	PI_{SLC}	NEB (eq. 3)	Standard LCA
GWP100	kg CO_2 eq	2.6E-01	4.0E-02	1.3E-01	8.8E-02	1.7E-01
Photochemical oxidation	kg C_2H_4	7.2E-05	8.4E-06	3.8E-05	2.6E-05	4.6E-05
Eutrophication	kg PO_4^{3-} eq	2.3E-02	1.4E-02	7.2E-06	9.2E-03	1.4E-02
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	5.2E-02	1.0E-02	7.3E-03	3.4E-02	1.7E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.1E+01	6.5E+00	3.4E+00	1.1E+01	9.8E+00
Human toxicity	kg 1,4-DB eq	5.5E-03	3.8E-03	3.4E-02	-3.3E-02	3.8E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	2.8E-04	1.9E-04	2.0E-02	-2.0E-02	2.0E-02
Acidification	kg SO2 eq	-	-	1.4E-04	-1.4E-04	1.4E-04
Abiotic depletion	kg Sb eq	-	-	1.1E-04	-1.1E-04	1.1E-04
Ozone layer depletion	kg CFC-11 eq	-	-	2.3E-09	-2.3E-09	2.3E-09

«1,4-DB eq»**:** 1,4-dichlorobenzene equivalent

NEB and standard LCA results comparison

Comparing the NEB and standard LCA results of table 5, it appears that both methods show the same results for impact categories only containing the potential impact caused by the WWTP's life cycle. For all other impact categories, the pollutant removal potential benefit expressed by the difference between rejecting wastewater without and with treatment allows showing positive potential environmental impacts of treating wastewater that are not overcome by the potential impacts generated by the WWTP's life cycle.

NEB potential applications

The NEB approach presented in this paper shows potential in helping to frame and interpret LCA in the field of wastewater treatment by taking into account more explicitly the function of the WWTP. The trade-off pointed out by the NEB allows presenting more explicitly the main function of a WWTP which is to obtain local and global environmental gains compared to rejecting wastewater without treatment at the expense of generated pollution by the WWTP's life cycle. In comparison to the NEB, a standard LCA only gives results for the potential impact generated by the WWTP's life cycle and treated wastewater rejection which sometime leads to see a WWTP as a major pollutant source of the integrated water system. The NEB not only allows taking into account the efficiency of the WWTP by assessment of the potential impact of rejecting water without treatment but also allows assessing the overall environmental performance of the WWTP by considering the impact of the WWTP's life cycle.

CONCLUSION

The NEB methodology requires the assessment of the potential impacts associated with rejecting wastewater, with and without treatment, and the potential impacts of the WWTP's life cycle by means of the LCA methodology. Compared to a standard LCA the NEB approach allows a clearer definition of the main function of the WWTP by representing the trade-off between the environmental benefit associated to the improved water's quality before rejection to the receiving water body and impacts generated by the WWTP's life cycle. NEB impact assessment results were compared to LCA standard results using the case study of a small municipal WWTP. Both methods showed the same results for impact categories containing only impacts generated by the WWTP's life cycle itself but differ in categories where wastewater treatment environmental benefit is accounted for. The NEB is a promising approach to more efficiently assess the environmental life cycle of a WWTP.

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