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Life Cycle environmental Assessment (LCA) of sanitation systems including sewerage: *Case of vertical flow constructed wetlands versus activated sludge*

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Abstract

The article presents the application of Life Cycle Assessment (LCA) to a complete sanitation system including the sewer network. It first describes the LCA hypothesis which concerns two types of waste water-treatment plant with the same daily nominal load in BOD₅ and associated to the same sewer network derived from the Life Cycle Inventory (LCI) database Ecoinvent. The two wastewater treatment systems compared are (i) a “Vertical Flow Constructed Wetlands (VFCW)” for which a detailed inventory was elaborated and (ii) an “activated sludge” stemming from the LCI database Ecoinvent. LCA scores of VFCW highlight the importance of eutrophication which can be easily explained by the incomplete removal of total N and total P in a VFCW. In a more surprising way, the impact of the network seems considerable. Finally, the article analyses the applicability and limitations of LCA for wastewater treatment with regard to water quality and the needed improvements of water status in LCA.

Keywords

Vertical Flow Constructed Wetlands, environmental impacts, LCA, sewerage, activated sludge, wastewater treatment plant.

INTRODUCTION

Assessing the environmental impacts of water sanitation systems may be done using the LCA approach (Life Cycle Assessment). Indeed, this “cradle to grave” approach includes all potential impacts from raw material extraction, manufacture, construction, use (including discharge), dismantling and disposal with all transportation steps induced by the operation of the sanitation system. The LCA approach aims at preventing a shifting of environmental consequences on several levels: (1) shifting between different impact categories (e.g. lessening an impact in Aquatic Eutrophication may increase relative impacts in Greenhouse Gas emissions and Resource Consumption); (2) shifting between different locations (e.g. from the pig house location to the land where the pig manure is spread) and, (3) shifting between several life cycle stages (e.g. improving the water treatment step may be done at the expense of the sludge end-of-life).

LCA has already been applied to classic Waste Water Treatment Plant (Renou, 2006) and wastewater sanitation systems (Doka, 2007). Application of LCA to Vertical Flow Constructed Wetlands (VFCW) is rarer in the literature (Dixon *et al.* 2003; Memon *et al.* 2007; Comby *et al.* 2009) and most of the available studies are assessing different systems of constructed wetland but do not compare VFCW with classic WWTPs including the sewer network and final water discharges. This article presents the application of LCA to a complete sanitation system including the sewer network. It first describes the Life Cycle Inventory and the main hypothesis which

concerns two types of WWTP with the same daily nominal load of 48kg BOD5.d-1 and the same associated sewer network derived from the Life Cycle Inventory (LCI) database Ecoinvent (Frischknecht et al. 2007).

METHOD

LCA is a method developed to carry out a comparison of environmental impacts of products, technologies or services on their whole life cycle, so called from “cradle to grave” (Haes *et al.*, 2002). The emissions to all environmental compartments and resource consumption during production, use and disposal are considered. The LCA framework is defined according to international standards (ISO 14040-14044) and for its effective implementation databases of processes, material and energy flows are used (Ecoinvent database in this study). The LCA method consists of 4 main phases described in this paper: (1) Goal and scope definition (2) Life Cycle Inventory - LCI (3) Life Cycle Impact Assessment – LCIA (4) Interpretation

Within the LCA conceptual framework, impact categories have been defined following the description of environmental pathways, i.e. cause-effect chains, as shown with some examples in Figure 1. This results in defining two main impact categories for Life Cycle Impact Assessment (LCIA), the first one being the MIDPOINT indicator category and the second being defined as ENDPOINT indicators. While midpoint indicators do not account for potential damages they may cause to the final targets, endpoint indicators are damage-oriented. They must be understood as issues of environmental concern, such as human health, extinction of species, and availability of resources for future generations. In this paper, the presentation of the results will use mainly midpoint indicators from the CML method (Guinée *et al.*, 2001) and in one case the endpoint Eco-indicator method (Goedkoop *et al.*, 2001).

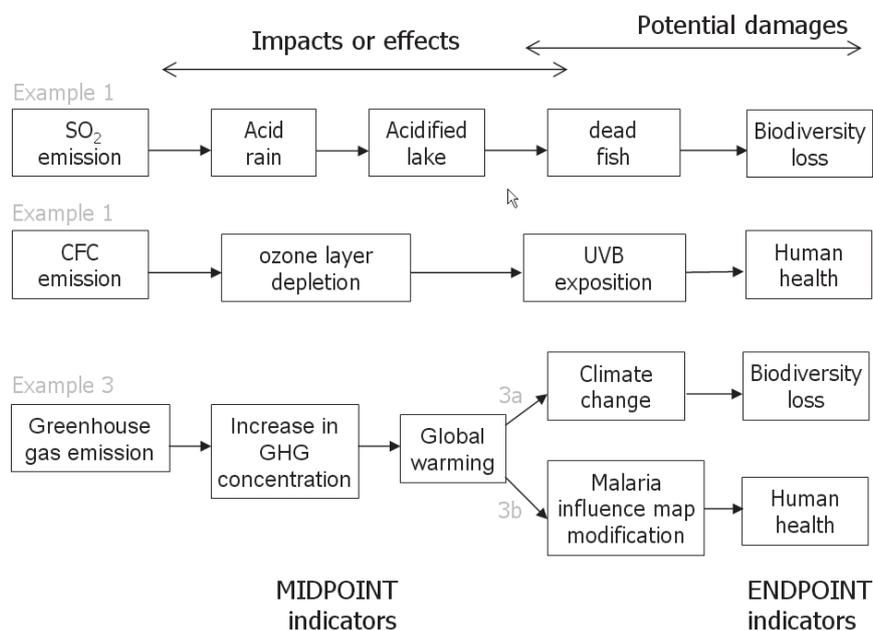


Figure 1. Examples of causality chains and indicators for environmental impacts.

LCA GOAL AND SCOPE

The first goal of the study was to compare a VFCW designed for about one thousand habitants with an equivalent common WWTP. This WWTP reference was chosen within the available ones in Ecoinvent database (Doka, 2007): a classic activated sludge, with a small capacity of 806 equivalent-habitants (class 5 in Ecoinvent database). The second goal of the study was to assess the

shares of the main contributors in a complete sanitation system including the sewer network which was also taken from Ecoinvent database (Doka, 2007). Finally, an unusual comparison with raw wastewater discharge to a receiving water body was carried out.

These goals result in the definition of three different systems to be studied:

- System A: “activated sludge” stemming from the LCI database Ecoinvent.
- System B: “Vertical Flow Constructed Wetlands (VFCW)” in 2 stages sized according to the usual French recommendations and for which a full detailed inventory of all materials and processes involved was elaborated.
- System C: raw wastewater discharge to the receiving water body without any prior treatment.

Functional unit

According to goal and scope definition, a key element has to be defined in LCA: the Functional Unit (FU) which is a measure of the function of the studied system. FU provides a reference to which all inputs (resource & energy consumption ...) and all outputs (emissions, by-products ...) can be related. This enables the comparison of two different systems providing the same service. The chosen functionality was “the amount of daily nominal organic load” (kgBOD₅) because it fits with the WWTP “sanitation function” and it has the advantage of being the only common point of the two plants assessed (same daily nominal load in BOD₅ : 48 kgBOD₅ · d⁻¹).

System boundaries

Finally, and always in accordance with the goal and scope of the study, the system boundaries have to be defined to determine which process units have to be included in the LCA as presented in Figure 2 for the three studied systems. It can be noted that the post-treatment of solid waste from pre-treatment stage is excluded from the system boundaries for systems A and B. Indeed, the solid waste will have the same end of life for these systems. For system C, only wastewater direct discharge is considered and as a first assumption solid waste is not taken into account. The sewer network is included in the system boundaries to assess its contribution, but it may be removed for some systems comparison to avoid masking effects.

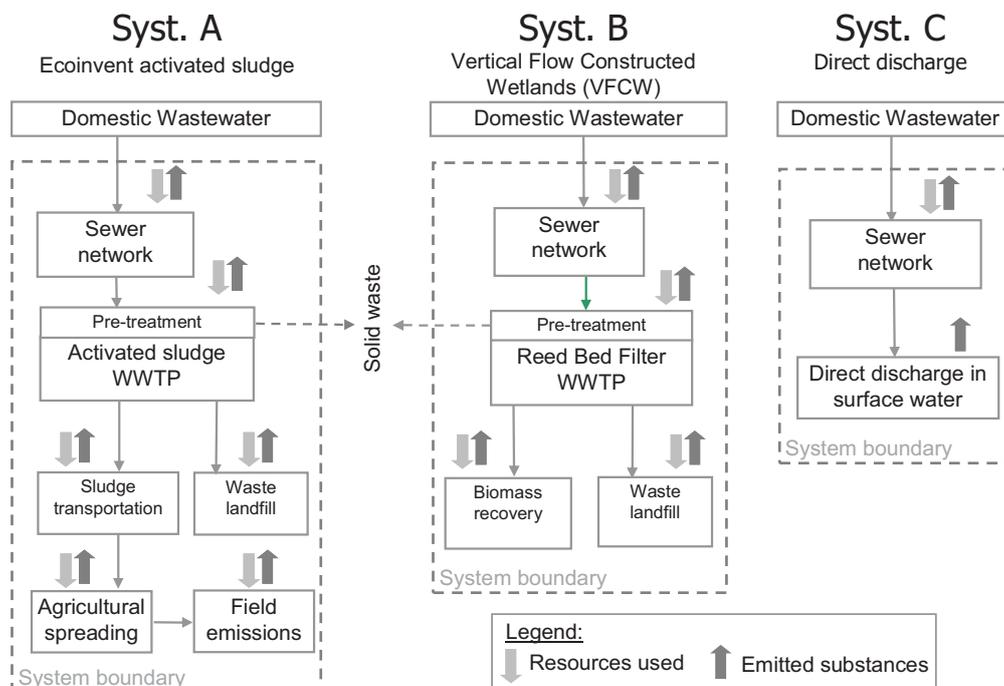


Figure 2. Waste Water Treatment Plants – process chains overview and systems boundaries.

SYSTEMS LIFE CYCLE INVENTORIES

A full LCA inventory including all resources used and all emissions on the entire life cycle was carried out for the VFCW. It is based on a VFCW sized according to the usual French recommendations (Boutin *et al.*, 1998; Molle *et al.*, 2004): first stage 60m x 20m made of three filters; second stage 56m x 14m made of two filters; including, all the distribution system, drainage network, liner, etc...

The first part of the inventory includes VFCW construction, maintenance, and dismantling. The level of detail of the inventory is quite fine and cannot be summarised in the present scientific paper but is available in a technical report (Dufour, 2009). The other part of the inventory concerns VFCW operation and include discharges. Table 1 presents the material input-output balance reflecting the efficiency of the VFCW. Balancing such a table is a very complex task which calls for specialist expertise and access to measurements data. The one presented in Table 1, is based on Cemagref expertise and available data (Molle *et al.*, 2004) and is really to be considered as a first basis to conduct this LCA of VFCW. In fact, most of the previous LCA approaches on constructed wetland systems (Dixon *et al.*, 2003; Memon *et al.*, 2007; Comby *et al.*, 2009) do not investigate such a precise input-output balance including water discharges. Indeed, this aspect can be overlooked if the purpose of the study is only to assess the contributions of the different life cycle stages of one specific WWTP. But if the study aims at comparing different systems such as a VFCW to conventional ones such as an activated sludge, the efficiencies of the studied processes (i.e. the discharged water) are not equivalent. So to find common ground for this second type of comparison, it is necessary to include the effluents because the service rendered by the sewage treatment plant is not the same (i.e. for the same input the outputs are different).

Table 1. Material input-output balance for the use phase of a FVFCW.

INPUT (wastewater content)		VFCW OUTPUTS (g.d ⁻¹ .hab ⁻¹) – water discharge and others outputs							Total output:
		Emissions and direct discharges		Sludge		Reeds			
Substances	g.d ⁻¹ .hab ⁻¹	Emissions to air	Emissions to water (discharges)	Emissions to air from sludge	Sludge content	Rhizomes	Reeds (above-ground)	Storage in the filter massif	
Nitrogen	N-NH ₄	7.50	0.16		0.70			0.11	10.0
	N _{org}	2.50	1.62				0.82		
	N-NO ₂	0.00							
	N-NO ₃	0.00	6.48						
	N-N ₂ O	0.00	0.11						
	N-N ₂	0.00							
N total =	10.00	0.11	8.26	0.00	0.70	0.00	0.82	0.11	
Phosphorus	P-PO ₄	1.60	1.50					0.01	2.00
	P _{org}	0.40					0.05		
	P-P ₂ O ₅	0.00			0.44				
	P total =	2.00	0.00	1.50	0.00	0.44	0.00	0.05	
Carbone	C _{org}	45.00	1.87		13.13				50.00
	C-CO ₂	0.00	16.79	13.05					
	C-CH ₄	0.00	0.09	0.07					
	C _{mineral}	5.00	2.00		3.00				
	C total =	50.00	16.88	3.87	13.12	16.13	0.00	0.00	

RESULTS AND DISCUSSION

Figure 3 present a Life Cycle Impact Assessment (LCIA) comparison of system A and B (without the sewer network) using CML midpoint indicators related to one kg of BOD₅ which is the chosen functional unit (FU). Calculated LCIA results have been normalised in this figure. Normalisation consists in the calculation of the magnitude of the results for an indicator category relative to some reference information (ISO 14040, 2006). In this figure it was done by dividing indicator results by 1990 global reference values and therefore the vertical axis of the graph is unitless. For instance, the amount of CO₂ equivalent (kg) emitted by the WWTP per functional unit (one kg of BOD₅ to be treated) is divided by the total amount of CO₂ equivalent (kg) emitted worldwide in 1990 (the result is dimensionless). Normalisation aims to better understand the relative magnitude for each indicator. This figure highlights for system B (VFCW) the importance of eutrophication which can be easily explained by the incomplete removal of total N and total P in a VFCW plant. Otherwise, the VFCW scores better than activated sludge in all other impact categories.

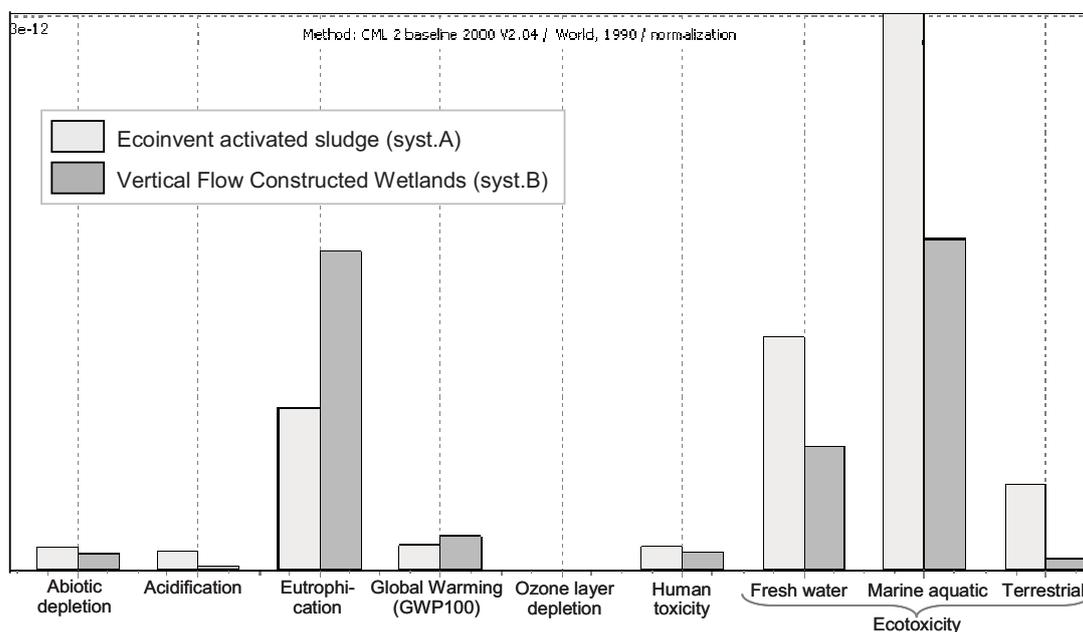


Figure 3. LCA results (mid-point indicators) – comparison system A versus B without the sewer network

Except for eutrophication (and to a lesser extent for Global Warming Potential), the comparison of the two systems shows a greater influence of system A (activated sludge) on all impacts categories. Nevertheless, this not surprising result has to be carefully assessed because the wastewater concentration and the hydraulic load are not the same in system A (data from Ecoinvent database) and system B (data from specific French situation) as shown in Table 2. This clearly highlights the limitation of LCA applied to the comparison of WWTP systems that are too different.

Table 2. Wastewater to be treated for each WWTP system.

Wastewater to be treated		Ecoinvent activated sludge	Vertical Flow Constructed Wetlands (VFCW)
Daily nominal organic load BOD ₅	kg. d ⁻¹	48.36	
	treatment capacity	806 PE*	967 habitants
Hydraulic load	m ³ . d ⁻¹	445	145
Water quality	BOD ₅	108.7	333.5
	COD	155.6	833
	Metals	yes	no

*PE : Person Equivalent : pollution equivalent to 60gBOD₅.d⁻¹

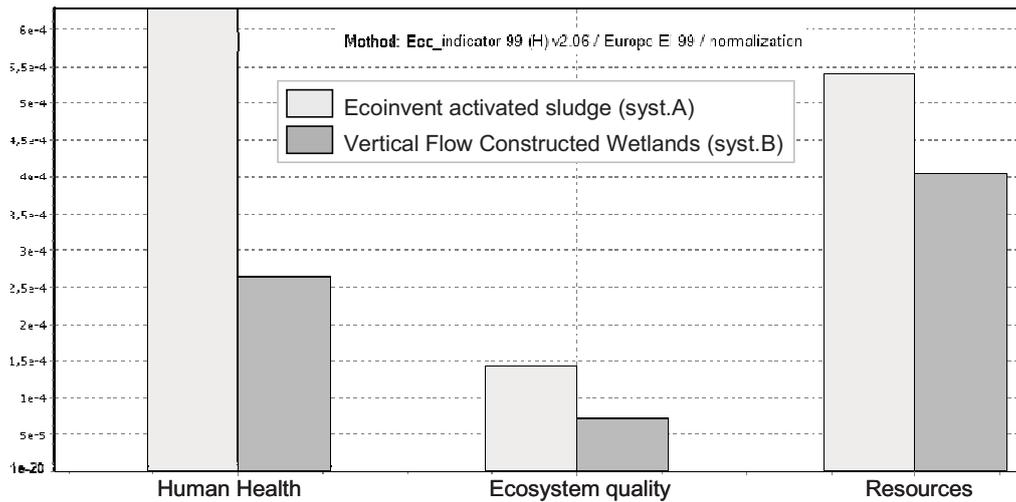


Figure 4. LCA results (end-point indicators) – comparison system A versus B without the sewer network.

Figure 4 presents the same normalised comparison as in Figure 3, this time based on endpoint indicators (Eco-indicator method). Lower impacts for system B (VFCW) are shown for the three damage categories per kilogram of BOD₅ (functional unit).

Figure 5 presents LCIA results for a global sanitation system including VFCW and sewer network. The main contributors of the VFCW life cycle stages (construction, use, dismantling, and discharge) as well as the connected sewer network are highlighted for each selected mid-point categories. In a surprising way, the impact of the network seems considerable in all impact categories except eutrophication and to a lesser extent Global Warming (categories affected mainly by water discharges).

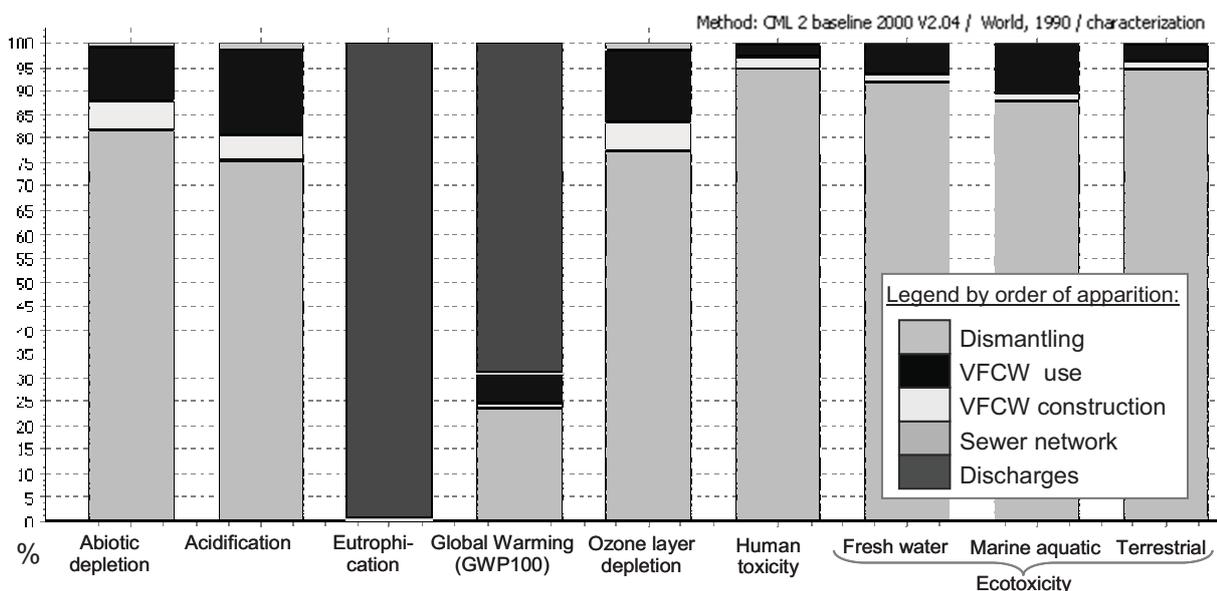


Figure 5. Main contributors for System B (VFCW) LCIA including sewer network.

Figure 6 continues with the unusual comparison of VFCW with raw wastewater discharge to the receiving water body. Comparing a WWTP with a direct discharge scheme as in Foley et al. (2010) is not so often commonly done with a multicriteria approach. In a very surprising way, the VFCW

midpoint indicators' scores are only slightly improved for eutrophication and are worse for all the other impact categories. Indeed, there are very interesting explanations and comments to be done to better understand such a surprising result. First of all, despite the great reduction in BOD5 achieved by the WWTP, the eutrophication potential remains very high compared to direct discharge. Eutrophication (Heijungs *et al.*, 1992) as assessed in LCIA with the CML method covers all potential impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). The Eutrophication Potential (EP) of a substance is based on the 'average' chemical composition of aquatic organisms: C106H263O110N16P assumed to be representative of average biomass. The only emissions considered to be eutrophying were emissions of P and N compounds. This approach determined the contribution of each of these nutrients to biomass formation, assuming unlimited supply of other nutrients. Hence, the characterisation factor for eutrophication is independent of whatever substance happens to be the limiting factor in a particular location. This approach (Guinée *et al.*, 2001) was adopted for two reasons: to obtain universal (i.e. global characterisation factors) independent of local differences, and because the sensitivity of the receiving environment is often unknown when comparing systems with LCA. As emissions of degradable organic matter have a similar impact, such emissions are also treated under the impact category 'eutrophication'. Based on this approach, the EP (in PO43- -equivalent) of the different substances discharged by WWTP are respectively EPCOD= 0.022, EPP= 3.06, EPN= 0.42, EPNO3- = 0.10,. It can be seen that COD has a relative low EP compared to P or N. In reality, when water is discharged in surface water, COD will result in eutrophication while P and N might grow biomass depending on the limiting nutrient, making eutrophication more or less likely to happen, or happening far away downstream the discharge point.

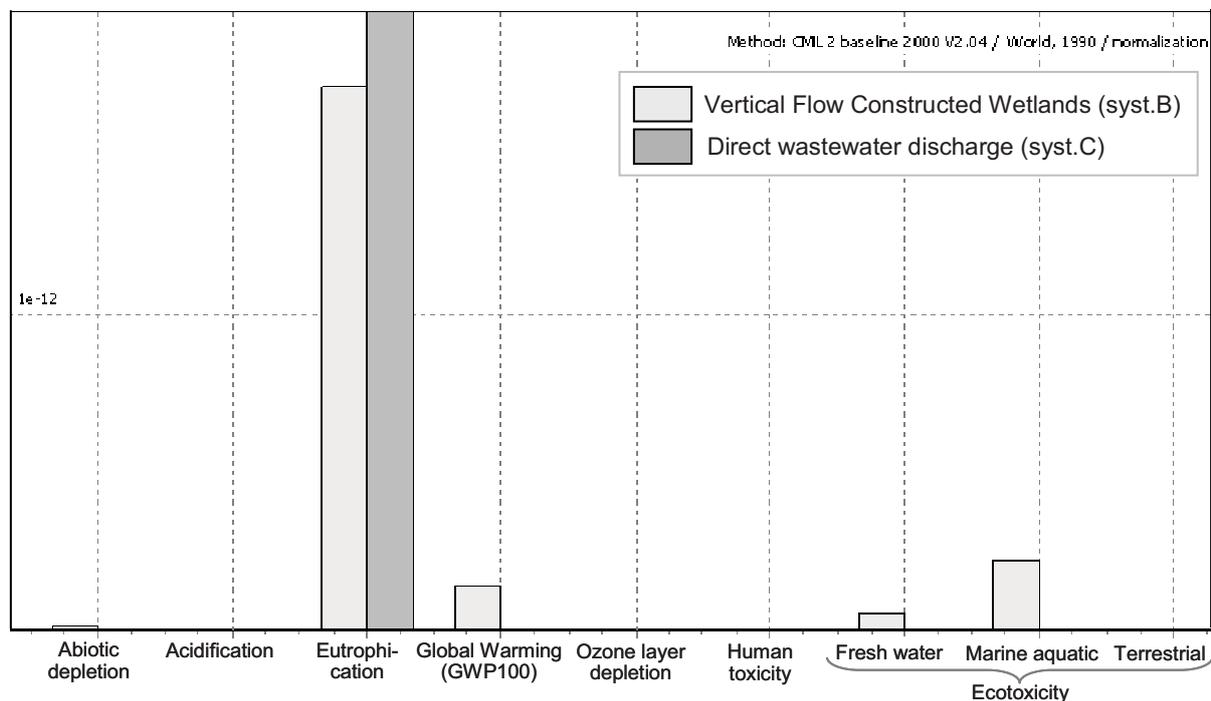


Figure 6. LCA results (mid-point indicators) – Comparison of system B (VFCW) versus C (direct discharge).

It is crucial, when analyzing Figure 6, to keep in mind that historically, the collection and treatment of wastewater has been carried out for health reasons (bacteria and various pathogens removal). Yet, these disease-inducing substances/organisms (also including emerging substances) are not

currently characterised in LCA neither for human toxicity nor ecotoxicity. Progress in LCIA (probably using end-point indicators) will radically change Figure 6 results by increasing toxicity and ecotoxicity indicators.

Finally, the effect of restoring to the natural environment treated water is not taken into account in Figure 6 because water is not yet considered as a resource in LCA. Very recent development in LCA (Bayart *et al.*, 2010; Pfister, 2009 ; Milà I Canals, 2009) have assessed the environmental impacts of freshwater consumption in LCA depending on water withdrawal sources (surface water, funds, stocks) and water usages (degradative and/or consumptive uses). Based on these results, a discussion should be initiated on the quantification of the positive impacts following the return of better quality water in the environment. Thus, the water outlet would be accounted for the actual avoided impacts “abiotic depletion” and may be for some other impact categories.

CONCLUSIONS AND PERSPECTIVES

Except for eutrophication, the comparison of the two systems (Vertical Flow Constructed Wetlands vs Activated Sludge) shows a smaller influence of system B (VFCW) on all impacts categories. Nevertheless, this not surprising result has to be carefully assessed because the wastewater quality and the hydraulic loads are not the same in Systems A and B (The 2 WWTP have the same organic loads.). This emphasizes the need to strengthen current LCI databases with WWTPs working in similar conditions (wastewater inputs) to enable common ground for a better comparison between systems. The other point highlighted in this study was the huge impact of the sewer network in all impact categories except for eutrophication, and to a lesser extent Global Warming. This also advocates the need to enrich LCI databases with sewer components in order to carry out the assessment of modular systems within centralised and/or decentralised scenarios.

Finally, this article analyses the applicability and limitations of LCA for wastewater treatment such as the aspect of water quality (including pathogens and other emerging substances) and the needed improvements with regards to the water status in LCA. Indeed, water has to be considered in LCA not only as an environmental compartment but increasingly as a scarce resource.

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