Life cycle assessment of wastewater treatment options for small and decentralized communities

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Water Science & Technology **Vol 56 No 3 pp 15–22**

Abstract Sustainability has strong implications on the practice of engineering. Life cycle assessment (LCA) is an appropriate methodology for assessing the sustainability of a wastewater treatment plant design. The present study used a LCA approach for comparing alternative wastewater treatment processes for small and decentralised rural communities. The assessment was focused on two energy-saving systems (constructed wetland and slow rate infiltration) and a conventional one (activated sludge process). The low environmental impact of the energy-saving wastewater treatment plants was demonstrated, the most relevant being the global warming indicator. Options for reduction of life cycle impacts were assessed including materials used in construction and operational lifetime of the systems. A 10% extension of operation lifetime of constructed wetland and slow rate infiltration systems led to a 1% decrease in CO_2 emissions, in both systems. The decrease in the abiotic depletion was 5 and 7%, respectively. Also, replacing steel with HDPE in the activated sludge tank resulted in a 1% reduction in CO_2 emission and 1% in the abiotic depletion indicator. In the case of the Imhoff tank a 1% reduction in CO_2 emissions and 5% in the abiotic depletion indicator were observed when concrete was replaced by HDPE.

Keywords Activated sludge; constructed wetland; life cycle assessment; slow rate infiltration; wastewater treatment

Introduction

Eco-efficiency is characterised by a continuous effort towards the improvement of economical and environmental values and a long-term need for sustainability. Therefore, the goals for wastewater treatment systems are moving beyond the protection of human health and aquatic ecosystems to include minimising loss of scarce resources, reducing the use of energy and water, reducing waste generation and enabling the recycling of nutrients (Lundin *et al.*, 2000). The Life Cycle Assessment (LCA) methodology has been used to explore the sustainability of wastewater systems, allowing a comparison of different technical solutions in terms of the estimated environmental loads (Emmerson *et al.*, 1995; Tillman *et al.*, 1998; Dennison *et al.*, 1999; Dixon *et al.*, 2003; Palme *et al.*, 2005). The wastewater treatment in rural areas requires decentralised systems and different options and technologies are available for such purpose. In this context, the present study was focused on the life cycle inventory and environmental impact evaluation of three wastewater treatment plants designs, namely an activated sludge process, a slow rate infiltration and a constructed wetland. The work was carried out within the frame of *DEPURANAT* –Sustainable wastewater management in rural areas, an EU project co-financed by Interreg IIIB Atlantic Arc Program.

doi: 10.2166/wst.2007.497

Methodology

Wastewater treatment plants

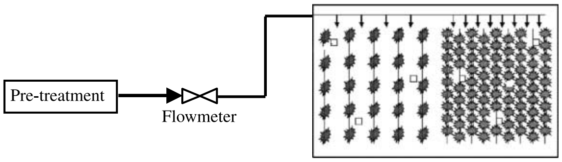
The wastewater treatment plants included in the scope of the present LCA study were a constructed wetland, a slow rate infiltration and an activated sludge process, all described briefly in Figure 1.

LCA methodology

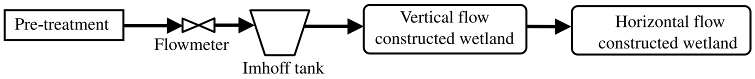
LCA is a quantitative methodology that evaluates the effects that a system has on the environment over the entire period of its life cycle. In general, it is a "cradle to grave" approach, including extraction, processing and manufacture, distribution, use, reuse, maintenance and disposal processes (Jensen *et al.*, 1997). LCA is described in the ISO 14040:1997 series, namely by ISO 14041:1997 standard – *Definition of objective, scope and inventory analysis*, ISO 14042:1997 standard – *Environmental impact assessment* and ISO 14043:1997 standard – Interpretation. SimaPro 7 software was used for the inventory and database on resources consumption and environmental emissions in the present LCA (PRé Consultants, 2006).

The LCA study comprised the production of components (equipments and accessories), construction and assembly, operation and maintenance and dismantling and final disposal of the wastewater treatment components. The system function concerned the legal standards stated by the Portuguese authorities for discharge in surface waters

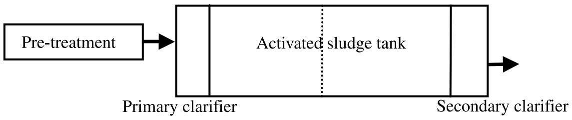
The slow rate infiltration plant[1] serves a population equivalent[*] of 40 p.e. in winter and 120 p.e. in summer and processes a flow rate of 5 m^3/d in winter and 15 m^3/d in summer. The system occupies an area of 2,000 m^2 and the biomass is *Populus euroamericana* (40) and *Eucaliptos camaldulensis* (214). The irrigation is provided by a PE piping system. The biomass is harvested every 5 years and the wood shredded in order to be used to produce pulp, later on.



The constructed wetland plant[1] serves a population equivalent of 120 p.e. and processes a flow rate of 15 m^3/d. The plant comprises a vertical flow, 317 m^2, and a horizontal flow, 277 m^2, constructed wetlands in series both with *Phragmites australis*. An Imhoff tank is used as pre-treatment. The following materials are used: i) geotextile lining; ii) gravel (support); iii) PE, PP and PVC (piping); iv) concrete and PVC (Imhoff tank). The biomass requires annual culling and the green waste is sent to a landfill. The sludge accumulated in the Imhoff tank is removed every 10 years and is used as soil amendment.



The activated sludge plant[2] is of the extended aeration type. It serves a population equivalent of 500 p.e. and processes a flow rate of 60 m^3/d. The activated sludge tank was constructed in inox steel AISI 306 and has two surface aerators, both functioning 11 h/d. The sludge is purged from the settling area and is used as soil amendment.



[1] Experimental plant of wastewater treatment, Carrión de los Céspedes (Spain)

[2] Municipal wastewater treatment plant (Portugal)

[*] One population equivalent (p.e.) has a daily biodegradable organic load of 60 g of oxygen per day expressed on a five-day biochemical oxygen demand

Figure 1 Description of the wastewater treatment plants

(40 mg/L as BOD, 150 mg/L as COD, 15 mg/L of ammonium and 10 mg/L of phosphorus), the functional unit was one population equivalent (p.e.) and the period of comparison was set at 10 years. Figure 2 depicts the system boundaries defined in the present study.

Results and discussion

Inventory analysis

Table 1 summarises the resources and emissions inventory of the different wastewater treatment plant designs. The materials used in the construction phase were considered to last for the whole life cycle of the plants, no replacement being considered for such purpose. The ultimate disposal site for the disassembled materials and wastes was assumed to be a landfill. The excess sludge purged from the treatment process was applied as soil amendment and the phosphorus and nitrogen avoided in land farming was calculated.

Impact assessment

The environmental impact assessment comprised three successive phases: classification, characterisation and normalisation. In the scope of this study the normalisation phase was not considered. In the classification step, all emissions were sorted into impact categories according to their environmental effects. Certain emissions were included in more than one impact category, as is the case of NO_x, which contributed to acidification and eutrophication. Subsequently, emissions within each impact category were aggregated using characterisation factors that compared the effect of a specific emission with a reference (PRé Consultants, 2006). The characterisation method was the *CML 2 Baseline 2000* because it is one of the few that consider nutrients (phosphorus and nitrogen) and organic matter as emissions. Table 2 presents the inventory results per impact category, expressed in relation to a functional unit of 1 p.e.

The most significant inventory elements that contributed to the environmental impact of the wastewater treatment plants displayed in Figure 2 were materials usage, energy consumption, CO_2 emissions and solid emissions.

Materials. In the present case study, the greatest quantities of materials used for plant construction were concrete (e.g. Imhoff tank), plastics (piping in all treatment systems and the geotextile membrane in the lining of the constructed wetland) and steel (activated sludge tank). All such items contributed to the impact category abiotic depletion because they use raw materials in their production and their production also involved the consumption of energy which contributed to the category global warming.

Energy. The energy usage of constructed wetland and slow rate infiltration systems is similar because both systems require a very low input. In contrast, the activated sludge

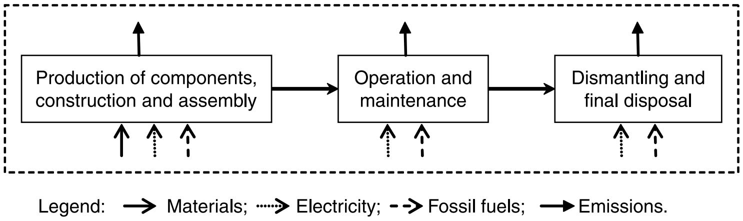


Figure 2 Boundaries of life cycle study

Table 1 Inventory results of wastewater treatment plants: constructed wetland, slow rate infiltration and activated sludge process (expressed in terms of 1 p.e.)

Inventory		**Constructed wetland**	**Slow rate infiltration**	**Activated sludge**
Resources				
Energy				
Fossil fuel	g	952	98	38
Electricity	kWh	–	–	321.2
Materials				
Gravel	t	10.8	–	–
Concrete		110.8 kg	0.073 m^3	–
Steel	kg	–	–	24.28
PVC	g	3,170	33.5	–
PP	g	642.5	121.5	–
Aluminium	g	16.7	25	–
PE	g	14.7	4,565	–
PET	g	–	–	153.7
Aluminium	g	16.7	25	–
Raw materials				
Gravel	kg	1.71	1.45	6.09
Iron	g	57.4	82.7	17,700
Sand	g	43.4	3.03×10^{-4}	0.0264
Nickel	g	2.96	5.27	10.5
Sodium chloride	g	2.39	0.0469	0.0303
Emissions				
To air				
Carbon dioxide	kg	−141	−956	592
Carbon dioxide (fossil)	kg	15.5	20.3	193
Sulphur oxides	g	785	112	154
Nitrogen oxides	g	169	117	118
Carbon monoxide	g	36.1	10.2	0.439
Sulphur dioxide	g	17.1	33.9	78.6
Carbon monoxide (fossil)	g	12.3	16.2	68.7
Nitrogen dioxide	g	11.5	–	–
Particulates	g	11.2	12.7	22.6
Propane	g	10.5	0.0925	2.3
Ethane	g	3.87	0.0674	3.7
Dinitrogen monoxide	g	0.263	2.24	72.9
Particulates ($<10\,\mu$m)	mg	61.5	6.33	244
To water				
COD	kg	68.5	68.5	68.5
Ammonium	kg	4.56	4.56	4.56
Phosphorus	g	456	456	456
Aluminium	g	56	3.66	65
Copper	mg	885	50	295
To soil				
Iron	g	0.24	0.17	3.6
Aluminium	mg	7.87	3.13	1,090
Waste				
Waste general	g	1,309	179	2,517
Chemical waste	g	69.4	2.083	464
Construction waste	mg	177	24.3	–
Sludge				
Total N	g	28.5	–	8.22
Total P	g	1.42	–	0.5

has much higher energy requirements because of the aeration equipment (22 h/d operation). These results agree with those reported by Dixon *et al.* (2003). Energy usage (fossil fuel and electricity) is the main contributor to the impact categories abiotic depletion and global warming which justifies the fact that activated sludge presents a higher impact in both categories.

Table 2 Inventory results per impact category of the wastewater treatment systems*

Emissions in each impact category	Impact categories and reference emissions	Value (kg)		
		Constructed wetland	Slow rate infiltration	Activated sludge
Aluminium	Abiotic depletion	48.2	39.3	323
Copper	Sb			
Iron				
Carbon dioxide	Global warming	-2.93×10^4	-1.87×10^5	4.01×10^4
Dinitrogen monoxide	CO_2			
Ethane	Ozone layer depletion	1.72×10^{-3}	1.2×10^{-3}	3.04×10^{-3}
Propane	CFC-11			
Carbon monoxide	Photochemical oxidation	3.25	2.61	17.8
Nitrogen dioxide	C_2H_4			
Sulphur oxides and dioxide				
Nitrogen oxides and dioxide	Acidification	31.1	38	434
Sulphur dioxide	SO_2			
Ammonium	Eutrophication	3.42×10^3	3.42×10^3	3.43×10^3
COD	PO_4^{2-}			
Dinitrogen monoxide				
Nitrogen oxides and dioxide				
Phosphorus				

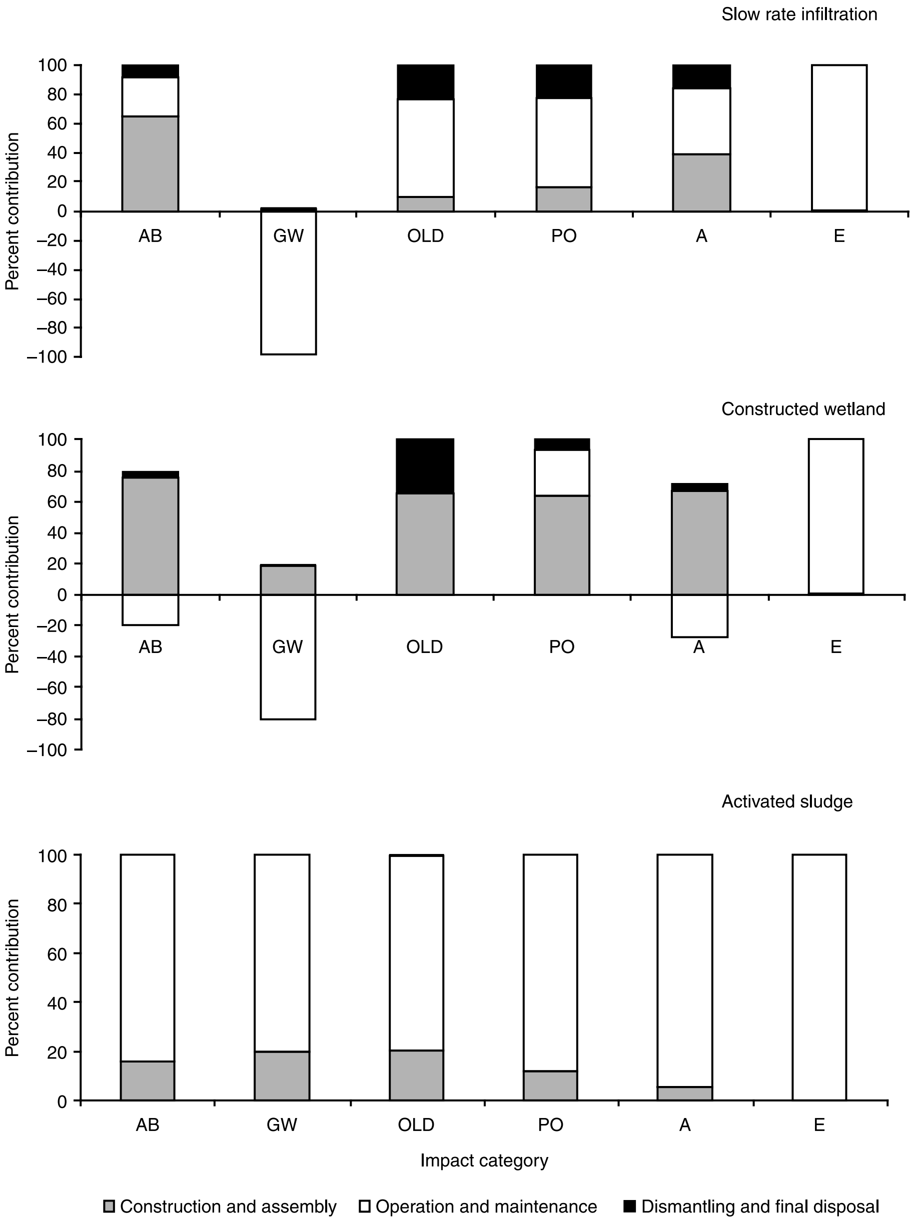
*The emissions presented in the first column are the ones that individually have the highest contribution within each impact category. The values presented in the third, fourth and fifth columns represent the sum of all emissions considered in each impact category

CO_2 emissions. The CO_2 emissions are directly related to the energy consumption. Again, the activated sludge system presented the highest environmental burden in the global warming category, when compared to the other systems, due to the high energy input for aeration. The constructed wetland and slow rate infiltration have significantly lower overall CO_2 emissions, due to the fact that biomass acts as a carbon sink, locking away atmospheric carbon. In particular, the slow rate infiltration system contributed to the decrease of the global warming factor.

Solid emissions. The main sources of solid emission resulted from the land excavated during construction and from the surplus sludge production during plant operation. Dixon *et al.* (2003) reported that the environmental impact of the soil removal can be reduced by its reuse in the infill in the dismantling phase. Sludge spreading on soil was the procedure applied by Lundin *et al.* (2000) in order to reduce environmental impacts. Such a procedure can only be considered in non-sensitive areas and might be questionable when large quantities are disposed of. The reuse of sludge translates into a reduction in abiotic depletion impact of constructed wetland and activated sludge systems.

Considering the whole life cycle of the wastewater treatment systems and the relative contribution of each phase – construction, operation and maintenance, dismantling and final disposal – their environmental impacts are presented in Figure 3. The analysis presented in Figure 3 reveals that activated sludge processes present the highest environmental impact during operation and maintenance because of the energy consumption required for aeration. A similar result was reported by Gaterell and Lester (2000). Slow rate infiltration and constructed wetland are advantageous when compared to the activated sludge system, not only because they use less energy during operation and maintenance, but also because they act as a carbon sink and the carbon balance is favourable. The dismantling and final disposal phase presents the lowest environmental impact. This result is congruent with the findings of Dixon *et al.* (2003). Gaterell and Lester (2000) reported that the environmental impact associated with demolition and disposal only contributes less then 20% of the total impact in conventional treatment systems. However, constructed wetlands display the most significant impact in the dismantling phase among the different wastewater treatment systems. Minimisation techniques are therefore important.

Maintenance and replacement schedules are expected to have environmental impacts when considering LCA methodology. However, as can be observed in Figure 3, because



AB	Abiotic depletion	GW	Global warming
OLD	Ozone layer depletion	PO	Photochemical oxidation
A	Acidification	E	Eutrophication

Figure 3 Contribution of life cycle phases of wastewater treatment systems to environmental impact categories

the life span of wastewater treatment plants is high, operation and maintenance phases present the major environmental impacts, instead of construction or disassembling ones. As a rule of thumb, many engineers use 10 years as the expected life span for mechanical equipment and 20 years for construction works/civil engineering, but Lundin *et al.* (2000) reported that pumps, tanks and other mechanical parts were expected to last for 15 years and buildings and pipes would last 30 years. Therefore, as a general guideline, wastewater plant designs with less replacement needs are favoured in terms of environmental impact along the life span of the systems, but greater accuracy in the results could be obtained through further testing of the direct emission reductions obtained with different replacement schedules. A 10% extension of operation lifetime of constructed wetland and slow rate infiltration systems leads to a 1% decrease in CO_2 emissions in both systems. The impact on the abiotic depletion is up to 5 and 7% decrease, respectively.

The effect of the materials used in the construction of activated sludge and Imhoff tanks (used as a pre-treatment in the constructed wetland), respectively steel and concrete, on the life cycle impact of the systems was assessed. In both units steel and concrete were substituted by HDPE, a material that can be used in construction. Replacing steel with HDPE in the activated sludge tank resulted in a 1% reduction in CO_2 emission and 1% in the abiotic depletion indicator. In the case of the Imhoff tank a 1% reduction in CO_2 emissions and 5% in the abiotic depletion indicator were observed when concrete was replaced by HDPE.

Conclusions

Design for sustainability is a key guideline during the planning phase and pre-selection of wastewater treatment plants, namely in decentralised systems located in rural areas. Innovation and design engineering of wastewater treatment processes can take advantage of LCA methodology. The present study reveals that the LCA approach can be used as a decision tool in design studies, but information for environmental impact assessment and minimisation measures need further improvement. In the present case, the LCA quantification identified the constructed wetland and the slow rate infiltration systems as appropriate technologies in rural areas. The key factor was the reduction of global warming impact due to carbon sequestration, as opposed to the activated sludge processes, which require a high energy input and present a negative carbon balance.

Acknowledgements

This work was supported by the European Union under the Program INTERREG III-B Atlantic Arc, DEPURANAT project (No. 54).

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