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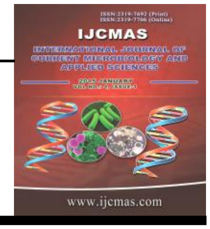

Original Research Article

Environmental Impact Assessment of Wastewater Treatment Plants - (Zenien and 6th of October WWTP)

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A B S T R A C T

Keywords

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Eco-indicator 99,
DALY

The main aim of this study is to assess the environmental impacts of two wastewater treatment plants (WWTP), located in Cairo, and to assess the influence of WWTP design capacity on the total environmental damage. The first WWTP (Zenien) is operated according to the secondary treatment with a capacity of 429000 m^3/day whereas the second WWTP (6^{th} of October) has a capacity of 150000 m^3/day and applies tertiary treatment. The Life Cycle Assessment (LCA) approach was adopted in the study to quantify environmental loading of the two plants using the Eco-indicator 99 methodology. The damages caused from the construction and operation of these environmental loads on human health, eco-system and resources were estimated. CO_2 emissions and energy consumption showed the highest environmental damage score also smaller capacity WWTP showed higher damage score per the adopted functional unit.

Introduction

Environmental problems have globally received more and more attention in recent years and efforts have been made to decrease these problems. As a result, efforts are being made to assess and understand causes of these environmental problems encountered in different human activities. Wastewater treatment systems have been designed to minimize the environmental impacts of discharging untreated wastewater in natural aquatic systems. Different wastewater treatment options have different performance characteristics and also different direct impacts in the environment. For instance, some systems have a higher energy usage, some use materials which have a high embodied energy (e.g. steel and cement), others occupy a greater expanse of land. If minimization of environmental impacts is one of the main functions of wastewater treatment systems then they should be designed so that their total impact on the environment is reduced (Dixon et al., 2003).

At any wastewater treatment plant (WWTP) there is an incoming wastewater flow; this flow is treated before it is allowed to be returned to the environment, lakes, or streams. Wastewater treatment plants operate at a critical point of the water cycle, helping nature defend water from excessive

pollution. Most treatment plants have primary treatment (physical removal of floatable and settleable solids) and secondary treatment (the biological removal of dissolved solids). Some other treatment plants have tertiary treatment option. The purpose of tertiary treatment is to provide a final treatment stage to raise the effluent quality before it is discharged to the receiving environment (sea, river, lake, ground, etc.). More than one treatment process may be used at any treatment plant.
The aim of this study was to assess the environmental impacts of two wastewater treatment plants, located in Cairo, of different capacities and different treatment methodologies. By identifying the sources of these impacts, it will be possible to propose solutions to improve the environmental performances of these plants.

Materials and Methods

Framework of study

To facilitate the comparison between the environmental burdens resulting from the two wastewater treatment plants, the Life Cycle Assessment (LCA) approach was applied using the Eco-indicator 99 methodology database. The Eco-indicator 99 does reflect the present state of the art in LCA methodology and application. The comparison is expressed in terms of the estimated environmental loads (Dixon et al., 2003; Palme et al., 2005). The damages caused by these environmental loads on human health, ecosystem quality and resources were estimated.

Scope of study

The LCA approach was applied to two treatment plants with different treatment capacities and technologies:

- *Zenein WWTP*: the plant has a capacity of 429,000 m^3/day and consists of three modules each is comprised of screening, grit removal, preareation, primary sedimentation, aeration, and secondary sedimentation units (Figure 1). The plant occupies an area of about 42 hectares.

- 6^{th} *October WWTP*: the plant has a capacity of 150,000 m^3/day and consists also of three modules each is comprised of screening, grit removal, primary sedimentation, aeration, sand filters and chlorine contact units (Figure 2). Area of 6^{th} of October WWTP is about 21 hectares.

Life Cycle Assessment (LCA) Approach

LCA of infrastructures such as buildings, roads, bridges and water treatment facilities has a few feathers compared with that of products; the object of analysis is complex facilities, and the life cycle span is 20~30 years and over. Thus, it is required to evaluate the environmental loads through the whole life cycle of the system consisted of compound structures and construction technique (Park et al., 2003). In general, LCA is composed of the following four steps; goal definition and scoping, inventory analysis, impact analysis, and improvement assessment (Park et al., 2003). Of these, impact analysis that evaluates plural different environmental loads with a same estimating index is very difficult and near to ideal, therefore has not been established yet in the methodology. Thus, current LCA is mainly performed with inventory analysis, which calculates the environmental loads generated from the step of getting raw materials to the step of waste, as a form of detail inventory. In this study, also, life cycle inventory of wastewater treatment was mainly analyzed.

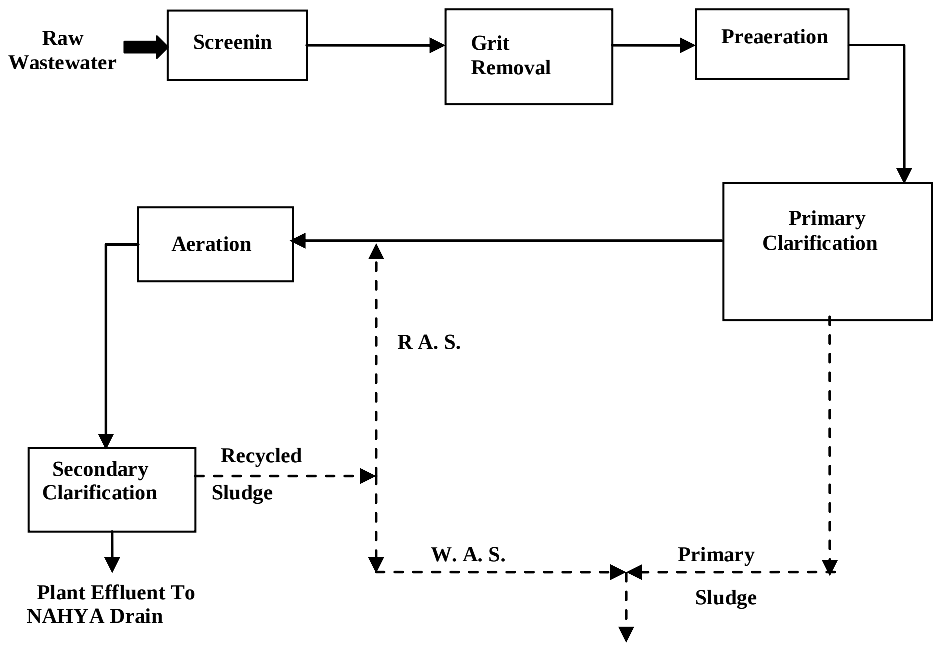

Figure.1 Process flow diagram of Zenein WWTP

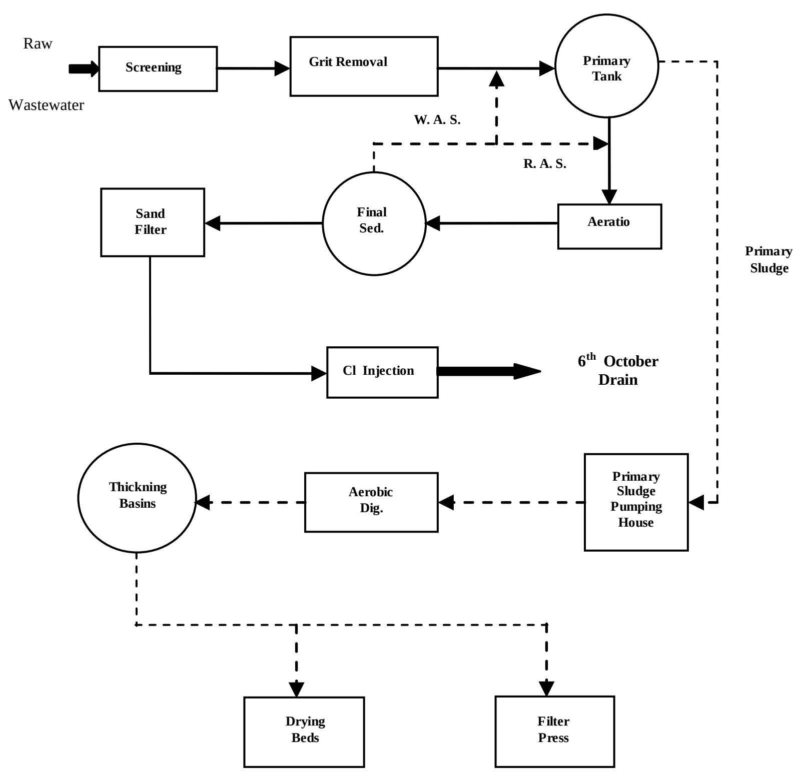

Figure.2 Process flow diagram of 6th October city WWTP

There are three ways utilized to quantify environmental loads (Life Cycle Inventory Analysis, LCI); process, input-output and hybrid analysis. Process analysis has been applied to analyze energy of individual products and materials, and input-output analysis to comparatively compound system and city (Park et al., 2003). In this study, hybrid analysis integrating above two analyses is applied. The life cycle environmental loads could be quantified using process analysis to the items comparatively easy to quantify such as machinery equipment, electric power, chemicals and fuels and input-output analysis to the rest (civil and construction work).

Functional Unit

Regarding the definition of the functional unit, several options may be taken into account such as the quantity of removed pollutants or the volume of the treated wastewater or the generated sludge (Hospido et al., 2008). However, the treatment of the wastewater generated from one person equivalent (pe) per year was adopted in this study as this parameter assists the comparison among different WWTPs (Tillman et al., 1998).

System Boundary

The system boundary shown in Figure (3) covers the construction and operation phases of the treatment plants. System boundary includes first-order environmental impacts, such as direct atmospheric emissions and effluent discharges. It also includes second-order impacts, such as the emissions and resources required for electricity generation and chemicals manufacture. This includes processes like cement and steel production and fuel consumption during their transportation to the construction site of waterworks, production of electricity and chemicals (chlorine) used in the operation phase. From literature, demolition phase contributed to less than 0.2% of total material and energy consumption (Friedrich, 2002) so was neglected in this study.

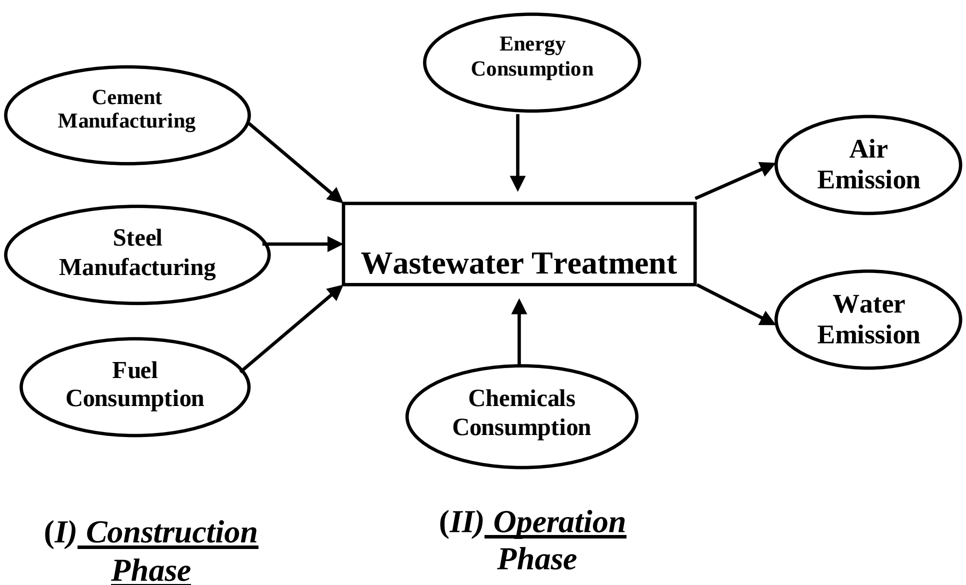

Figure.3 System boundary and impact categories

Life Cycle Inventory Analysis

The construction phase data were collected from the two wastewater treatment plants including the cement and steel quantities needed for their construction, energy and raw materials consumed in manufacturing these materials, air and water emissions induced during their manufacturing, fuel consumption during the transportation of these materials to construction site (see Appendix). The operation phase inventory data was based on electricity and chemicals quantities consumed during the operation of the treatment plant through the life time of the WWTPs. It also included the induced emissions during the generation of required electricity and manufacturing of consumed chemicals (Nicolay, 2000; Spath and Mann, 2000; IPPC, 2001a,b).

Consumed materials in the construction and operation processes of the two WWTPs are shown in Tables (1& 2) summarize estimated main air emissions induced during the construction and operation through the lifetime of both treatment plants (assumed to be 40 years).

Life Cycle Impact Assessment

Damage factors of each emission to air and water were adopted from Eco-indicator 99 methodology database (Goedkoop and Spriensma, 2001). Water emissions showed negligible damage effect compared to air emissions. Finally, the impact from each process on human health, ecosystem quality and resources consumption were quantified. Calculated damage scores on human health, ecosystem quality and resources consumption revealed the following results:

Human Health

Damage to human health included emissions such as: carcinogenic emissions, climate change, ozone layer depletion, organic and inorganic substances causing respiratory effects. The concept of disability adjusted life years (DALYs) was used to quantify human health risk from both WWTPs. DALYs is one of the indicators for measuring aggregated health losses, and combines years of life lost with years lived with disability that are standardized by means of severity weights (Murray and Lopez, 1996; Aramaki et al., 2006). Emissions causing health risks from main processes during construction and operation phases were quantified. Table 3 presents an example of the impact of those emissions from cement consumption during the construction phase of WWTPs. Among the emissions with significant effect to human health; CO_2 emissions caused the highest damage. Large CO_2 emissions are produced during cement manufacturing and electricity production. Figure (4) presents the emissions with higher damage score on human health from both WWTPs.

Ecosystem Quality

Damage to ecosystem quality assessed in the study included ecotoxic emissions, combined effect of eutrophication and acidification emissions as well as land occupation of the WWTPs. The ecosystem quality damages are expressed as the percentage of all species that have disappeared in a certain area due to environmental loading and they are specified as PDF.m^2.yr. PDF is short for Potentially Disappeared Fraction of Species. A damage of one means all species disappear from m^2 during one year, or 10% of all species disappear from 10 m^2 during one year, or 10% of all species disappear from 1m^2 during 10 years (Goedkoop and Spriensma, 2001). Table (4) presents the impact on ecosystem due to ecotoxic emissions, combined effect of eutrophication and acidification emissions from cement industry.

Table.1 Consumed materials and energy in construction and operation phases

Phase	Process	Zenien WWTP	6th of October WWTP
Construction Phase	Consumed Fuel (lit.)	259460	113340
	Consumed Cement (t)	280212	240000
	Steel (t)	14011	12000
Operation Phase	Energy (GWh)	2803.2	1401.6
	Chlorine (t)	6263.4	1095

Table.2 Induced main emissions through lifetime of both treatment plants

Airborne Emissions	Zenien WWTP	6th of October WWTP
NOx [kg/m^3]	4.8	2.5
SOx [kg/m^3]	4.3	2.7
CO_2 [t/m^3]	4.65	0.73
VOC [kg/m^3]	1.25×10^{-2}	4.1×10^{-4}
NH_3 [kg/m^3]	1.7×10^{-4}	5.5×10^{-6}
Ni [kg/m^3]	2.4×10^{-4}	1.6×10^{-4}
Particulates [kg/m^3]	9.4×10^{-3}	3.1×10^{-5}

Table.3 Impact of cement in construction phase (Human Health)

Compartment	Emission	Average emission kg/ton (E)	F1	F2	F3	∑F	∑F*E DALYs/ton
Air	**NOx (as NO_2)**	2.4	-	8.87E-05	-	8.87E-05	21.288E-05
Air	**SO_2**	2.6	-	5.46E-05	-	5.46E-05	14.196E-05
Air	**CO_2**	690	-	-	210E-07	-	144900 E-07
Air	**Dust**	0.154	-	7E-04	-	7E-04	1.08E-04
Air	**Ni**	0.00015	2.35E-02	-	-	2.35E-02	3.53E-06
Water	**Ni**	0.00015	3.11E-02	-	-	3.11E-02	4.7E-06
Total							**0.015 (air) 4.7E-06 (water)**

F1: Damages to Human Health caused by carcinogenic substances, kg/DALY
F2: Damages to Human Health caused by respiratory effects by inorganic substances. kg/DALY
F3: Damages to Human Health caused by climate change. kg/DALY

Table.4 Impact of cement in construction phase (eco-system quality)

Compartment	Emission	Average emission kg/ton (E)	F1	F2	∑F	∑F*E
Air	NOx (as NO_2)	2.4	-	5.713	5.713	13.7112
Air	SO_2	2.6	-	1.041	1.041	2.7066
Air	Hg	0.0002	8.29E02	-	8.29E02	0.17
Air	Ni	0.00015	7.1E03	-	7.1E03	1.1
Air	Pb	0.00045	2.54E03	-	2.54E03	1.14
Water	Hg	0.0002	1.97E02	-	1.97E02	0.04
Water	Ni	0.00015	1.43E02	-	1.43E02	0.022
Water	Pb	0.00045	7.39E00	-	7.39E00	3.33E-03
Total						**18.83 (air)** **0.065 (water)**

F1: Damage to ecosystem quality caused by ecotoxic emissions.
F2: Damage to ecosystem quality caused by the combined effect of acidification and eutrophication.

Table.5 Total damages to resources [MJ energy] from both WWTPs

Process	Zenien WWTP	6^{th} of October WWTP
Cement	1.23×10^{8}	1.1×10^{8}
Steel	1.1×10^{6}	9.4×10^{4}
Fuel Consumption	2.8×10^{6}	1.6×10^{6}
Energy Consumption	1.5×10^{9}	7.6×10^{8}

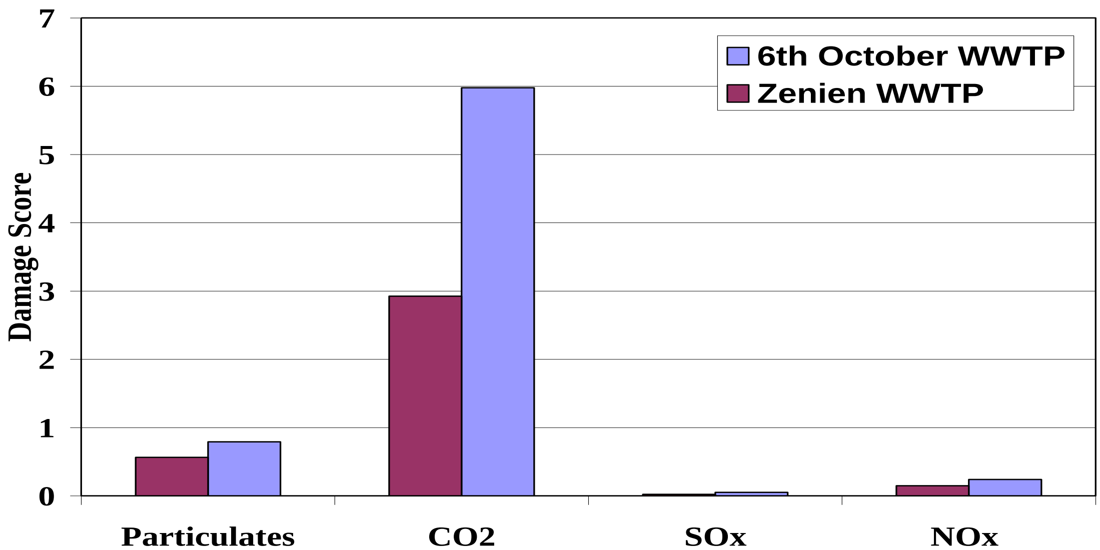

Figure.4 Emissions having higher damage score on human health from the two WWTPs

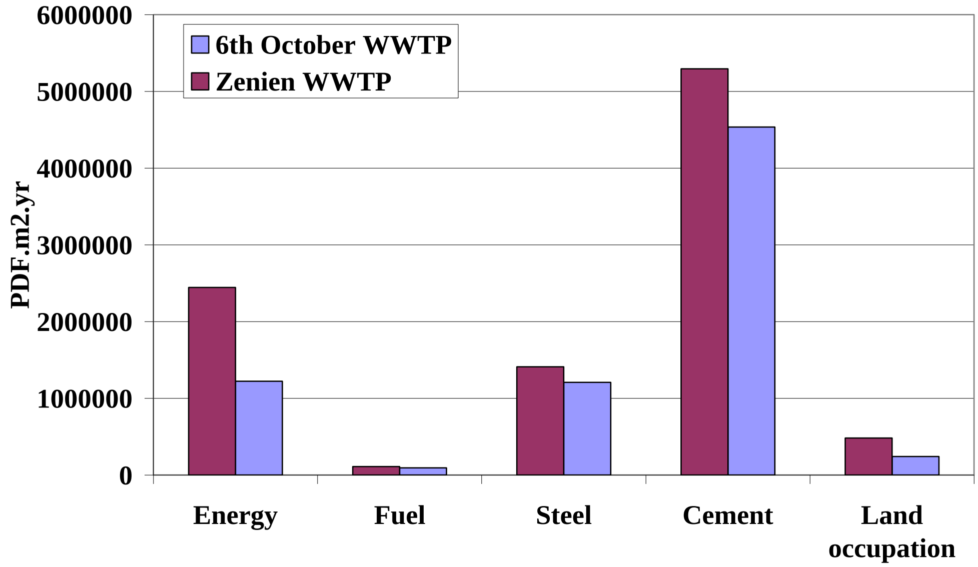

Figure.5 Damage values [PDF.m^2.yr] ecosystem quality for both WWTPs

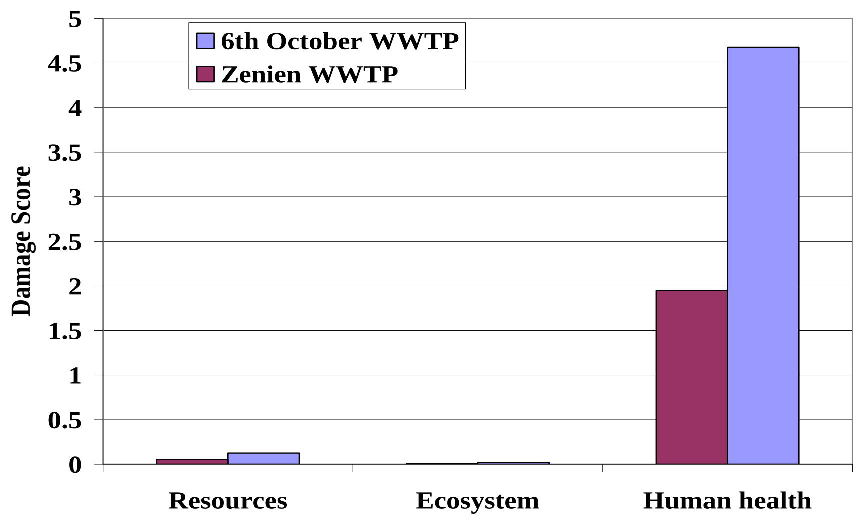

Figure.6 Normalized damage scores from both WWTPs to different impact categories

Table.6 Total damages from construction and operation phases in both WWTPs

Phase	Process	Zenien WWTP	6^{th} of October WWTP
Construction Phase	Consumed Fuel	1.3×10^5	9×10^4
	Consumed Cement	1.1×10^8	9.6×10^7
	Steel	4.2×10^5	3.8×10^5
Operation Phase	Energy	4.6×10^7	2.3×10^7
	Chlorine	6.0×10^4	1.0×10^4
Total Normalized Damage Score		2.0×10^8	1.4×10^8
Total Normalized Damage Score per FU		73.24	144.86

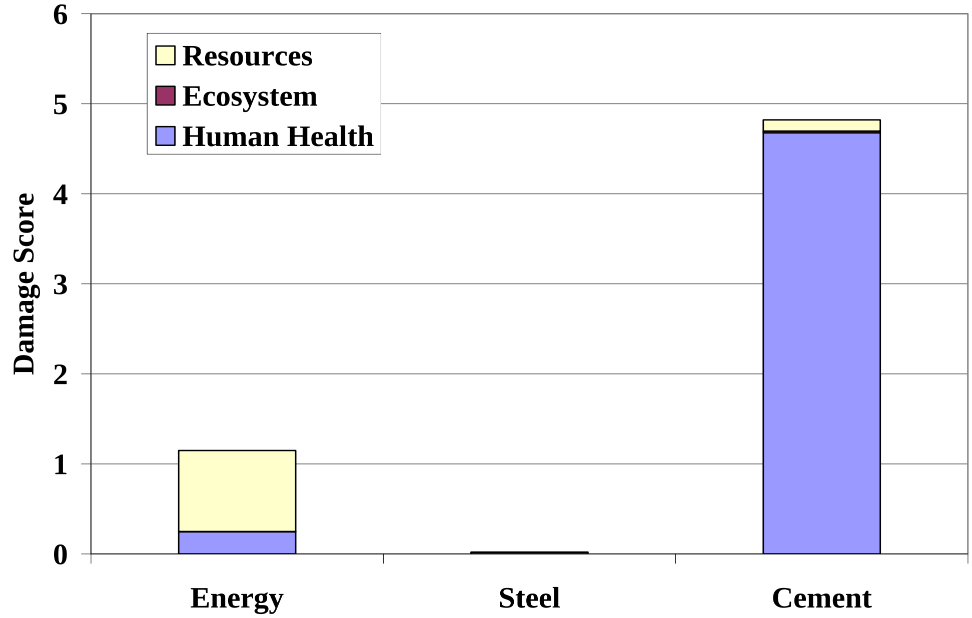

Figure.7 Impact of different construction and operation processes on different impact categories and overall damage from 6th of October WWTP

The damage to ecosystem quality caused by land occupation (F3) is calculated according to the total area, in m^2, of the WWTP. The damage factors is 1.15 (i.e. continuous urban land). The total damage by land occupation for a WWTP is given as: 1.15 * plant area

Area of 6th of October WWTP = 210000 m^2

Area of Zenein WWTP = 420000 m^2

F3 (6th of October WWTP) = 1.15 * 210000 = 241500 PDF. m^2.yr

F3 (Zenin WWTP) = 1.15 * 420000 = 483000 PDF . m^2. yr

Highest damage to ecosystem quality was from NOx, SOx and ecotoxic emissions (Pb and Ni) emitted during cement and steel manufacturing. Higher materials and energy consumptions and larger land occupation of Zenien contributed to higher environmental loading than 6th of October WWTP. Figure (5) compared the damage values of processes contributing to ecosystem quality damage for both WWTPs.

Resources Consumption

Minerals and fossil fuels consumptions during the construction and operation processes of each WWTP were identified as the main sources of resource consumption. Production of electricity was assumed to be based on natural gas powered plants as the usual practice of electricity production in Egypt. Damage factors are expressed in MJ surplus energy per kg extracted material for minerals and in MJ surplus energy per kg of extracted fuel, or per m3 of extracted gas, or per MJ extracted energy for fossil fuels (Goedkoop and Spriensma, 2001).

As an example; damage to resource by extraction of fissile fuel by cement industry is computed as follows:

- The electricity demand is about 90-130 kWh/tonne cement. Taking an average value of 110 kWh/tonne cement. The electricity consumed in cement industry is taken from natural-gas operated power plants. Hence, the damage factor to resources according to Ec0-methodology 99 is 1.5E-01in MJ.

Therefore, the damage per tonne cement (caused by electricity demand) is given by

1.5E-01 * 110* 3.6 = 59.4 MJ/tone cement

- The mass balance for the production of 1kg cement indicates that 0.75 kg of clinker is needed. And, as the process for producing cement in Egypt is dry process rotary kilns equipped with cyclone preheaters, then for the production of 1 ton clinker 3100-4200 MJ are required. Taking an average value of 3650 MJ/ton clinker gives an energy consumption of 2740 MJ/ton cement. The used fuel is heavy fuel oil. The damage factor to resources according to Eco-methodology 99 is 5.9 per kg fuel.

Mass of fuel consumed per tonne cement is 2740/ (Calorific value of fuel)

As the calorific value of fuel is 42640 kJ/kg.

Therefore, mass of fuel consumed = 2740E06/42640E03

= 64.3 kg fuel

Therefore, the damage per tonne cement (caused by heavy fuel oil demand) is given by

5.9 * 64.3 = 379.4 MJ

Total damage to resource by extraction of fissile fuel by cement industry, per tonne cement is given as

59.4 +379.4 = 438.8 MJ/tonne cement

Energy production needed for the operation of WWTPs contributed to the highest damage to resources in this study as shown in Table (5).

Result and Discussion

Comparing the total damages of the two WWTPs (Table 6); Zenien plant showed higher total damage scores as it had a larger capacity and applies advanced treatment and hence it consumes larger quantities of chemicals and energy than 6th of October WWTP. However, calculating the total damage scores to both plants with respect to the functional unit (i.e. damage per person.yr); Zenien contributed to less total damage than the 6th of October WWTP having smaller capacity. This result emphasizes the role played by the design capacity of WWTPs on environmental impact. As different damage categories have different units, normalization was considered. By normalization it is meant that a set of dimensionless weighting factors are used to express different damage categories. Normalized total damage score from construction and operation processes of both WWTPs are also shown in Table (6).

Comparing between environmental loading on different impact categories (i.e. human health, ecosystem quality and resources consumption); damage from construction and operation of WWTP mainly impact the human health category as shown in Figure (6). This can be attributed to high emission factors of greenhouse gases (mainly CO_2 and CH_4) emitted during cement and energy production. However, highest damage to resources resulted from energy consumption in operation process. Comparing the environmental loading from different processes involved in the operation and construction of WWTPs; cement manufacturing contributed to the highest emissions of CO_2, NOx and SOx causing the highest environmental loading impact and affecting mainly human health as shown in Figure (7) for 6th of October WWTP. Fuel consumption during transportation of construction materials, steel manufacturing and chlorine production showed negligible effect compared to other processes such as cement and energy production.

This research was concerned with performing environmental assessment of two WWTPs applying secondary treatment process (Zenien WWTP) and tertiary treatment process (6th of October WWTP), by means of Life Cycle Assessment technique (LCA). The aim of the study is to compare and quantify the environmental loading from two different treatment technologies and two different sizes of WWTP. The study revealed the following conclusions:

- LCA is an effective environmental tool which can allow the estimation and quantification of possible environmental damages related to a wastewater treatment process.
- Design capacity of WWTPs plays an important role in the environmental loading, moving to larger capacities reduces overall damages to human health, ecosystem quality and resources consumption.
- The comparative study carried out has shown that the different configurations regarding the wastewater treatment processes affect the environmental performance of a wastewater treatment plant.
- Electricity use and cement manufacturing plays an important role in the environmental assessment of a WWTP.
- CO_2 emissions contributed to the highest damage on impact categories especially human health.
- The need to have some international values of environmental reference damages to compare with when a LCA study is performed.

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