Using Life Cycle Assessment (LCA) to Assess the Sustainability of Urban Wastewater Treatment Systems: a Case Study of the Wastewater Treatment Technology of the Bogotá River

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Using Life Cycle Assessment (LCA) to Assess the Sustainability of Urban Wastewater Treatment Systems: a Case Study of the Wastewater Treatment Technology of the Bogotá River

Uso de la Evaluación de Ciclo de Vida para el Análisis de la Sostenibilidad de Sistemas de Tratamiento de Aguas Residuales Urbanas: Un Estudio de Caso de la Tecnología de Tratamiento de las Aguas Residuales del Rio Bogotá.

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ABSTRACT

Sustainable development indicators (IDS) based on the methodology framework of life cycle Assessment (LCA) was used to assess the El Salitre wastewater treatment Plant (WWTP) in Bogota, Colombia, instead of the environmental impact assessment (EIA) most commonly used. Understand impact as the multiple effects that any technological system has on the environmental, economic and socio-ecological systems, a set of four categories of IDS were developed and applied in order to investigate the overall sustainability of the WWTP Salitre, which are, functional, environmental, economic and socio-cultural. The data used were collected from both the water and the sludge lines between 2004 and 2010 from the records supplied by the operator of the WWTP.

The functional indicators applied were effectiveness, efficiency, flexibility, maintenance required, and reliability. The environmental indicators used to evaluate the plant’s environmental performance included effluent quality, sludge quality, global warming potential (GWP) from gaseous emissions, nuisance and public health risk. Cost effectiveness (total, operational, maintenance and energy costs per volume of wastewater treated) and user cost were used as the economic indicators while aesthetics, public participation with regards to the stimulation of sustainable behavior by increasing the end-user's awareness, participation, and responsibility evaluated by number of visits to the plant, expertise (level of education) and labor required to operate plant were applied as the socio-cultural indicators.

The results showed that the plant has a varying degree of sustainability and adaptability and improvements can be achieved by adopting appropriate best management practices (BMPs) in all the four dimensions of sustainable development in accordance with the selected indicator categories.

Key words: Sustainability, Sustainable development indicator (SDI), life cycle assessment (LCA), best management practices (BMP).

RESUMEN

Se utilizaron Indicadores de Desarrollo Sostenible (IDS) con base en la metodología del Análisis de Ciclo de Vida (ACV) para evaluar la Planta de Tratamiento de Aguas Residuales PTAR El Salitre, ubicada en Bogotá, Colombia, en vez de la herramienta de Evaluación del Impacto Ambiental (EIA) más comúnmente empleada. Para comprender el impacto en el sentido de los múltiples efectos que cualquier sistema tecnológico tiene sobre los aspectos ambientales, económicos y socioculturales de los sistemas ecológicos, se desarrolló y aplicó un conjunto de cuatro categorías de IDS con el fin de investigar la sostenibilidad general de la PTAR El Salitre, a saber: funcional, ambiental, económica y sociocultural. Los datos utilizados fueron recogidos tanto en la línea de agua como en la de lodos, en el período 2004 a 2010, a través de la consulta de los registros suministrados por la administración de la PTAR.

Los indicadores funcionales aplicados fueron: Eficacia, eficiencia, adaptabilidad, y el mantenimiento requerido. Los indicadores ambientales utilizados incluyeron la calidad del efluente, calidad de los lodos, emisiones de gases asociados al calentamiento global (CG), molestias y riesgos para la salud pública. Los costos de operación, mantenimiento, energía y los costos para el usuario por metro cúbico de agua residual tratada se utilizaron como indicadores económicos, mientras que la participación ciudadana, la estética, la estimulación de un comportamiento sostenible, y la participación de la comunidad evaluada por el número de visitas a la planta fueron los indicadores socio-culturales.

Los resultados mostraron que la planta tiene un grado variable de sostenibilidad y que la capacidad de adaptación y las mejoras se pueden lograr mediante la adopción de mejores prácticas de manejo (MPM) en todas las cuatro dimensiones del desarrollo sostenible de acuerdo con las categorías de indicadores seleccionados.

Palabras clave: Sostenibilidad, el indicador de desarrollo sostenible (IDS), la evaluación del ciclo de vida (ACV), las mejores prácticas de manejo (MPM).

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ACRONYMS AND ABREVIACIONES

ADWF:	Average Dry Weather Flow
AAU:	Urban Environmental Authorities (*Autoridades Ambientales Urbana*)
BMP:	Best Management Practices
BOD_5:	5-day Biochemical Oxygen Demand
CAR:	Regional Autonomous Corporations (*Corporación Autónomas Regional*)
CC:	Chemical Cost
CH_4:	Methane
CO_2:	Carbon dioxide
COD:	Chemical Oxygen Demand
DAMA:	Technical Department for Environmental Aministration *(Departamento Técnico Administrativo del Medio Ambiente)*
EAAB:	Bogotá Water and Sewage Company (*Empresa de Acueducto y Alantarillado de Bogotá)*
EC:	Energy Cost
EF:	Ecological footprint
EIA:	Environmental Impact Assessment
ERA:	Environmental Risk Assessment
GHG:	Greenhouse Gas
GW:	Global Warming
GWP:	Global Warming Potential
H_2S:	Hydrogen sulfide
LCA:	Life Cycle Assessment
LCIA:	Life Cycle Impact Assessment
MAVDT:	Ministry of Environment, Housing and Developemnt (Ministerio del Ambiente, Vivienda y Desarrollo Territorial)
MMA:	Ministry of Environment (Ministerio de Medio Ambiente)
N:	Nitrogen
N_2O:	Nitrous oxide
OMC:	Operational and Maintenance Cost

P:	Phosphorus
PA:	Positional Analysis
PE:	Population Equivalent
PHR:	Public Health risk
PWWF:	Peak Wet Weather Flow
Q:	Flow rate
SD:	Standard Deviation; Sustainable Development
SDI:	Sustainable Development Indicator
SEA:	Strategic Environmental Assessment
SS:	Suspended Solid
SWWM:	Sustainable Wastewater Management
TC:	Total Cost
TKN:	Total Kjeldahl nitrogen
TMR:	Total material requirement
TN:	Total Nitrogen
TP:	Total Phosphorus
TS:	Total Solid
TSS:	Total Suspended Solid
UC:	User Cost
VS:	Volatile Solid
VSS:	Volatile Suspended Solid
WCED:	World Commission on Environment and Development
WSP:	Waste Stabilization Pond
WW:	Wastewater
WWTP:	Wastewater Treatment Plant
WWTS:	Wastewater Treatment System

1 INTRODUCTION

Engineering solutions have often been described to be vital to solving environmental, sanitation and health quality problems. As such, these technological solutions have been sort to bring about the much needed solutions especially with respect to achieving a sustainable urban wastewater management especially with emerging municipal wastewater management problems and social pressure (hygiene, flooding of cities, and protection of the aquatic environment). Large cities in developing countries, where population is on the rise, are increasingly seeking this solution by incorporating the convectional centralized wastewater treatment plants (WWTP), an approach imported from the developed countries, to create a sustainable urban watershed management. According to Zhang et al. (2010), there is an urgent need for urban water and wastewater management improvement given that by 2025 about sixty percent of the world's population will live in urban areas. This is particularly true given that the adaptability of these technologies to both the socio-ecological system and the technologies' flexibility to accommodate changes and uncertainties now defines their sustainability.

In line with this, Muga and Mihelcic, (2008) argued that the adverse alteration in an urban ecosystem's hydrology, increased energy and maintenance requirement and the requirement for extensive infrastructure from the transport of water and wastewater across watershed boundaries (considering the fact that the discharge of large volumes of treated wastewater that contains low levels of chemical constituents) still pose a significant threat to a receiving water body from excessive input of nutrients. Sustainability, therefore, "challenges us to reflect on wastewater treatment differently" (Balkema et al., 2002). A paradigm shift that focuses on treatment processes and results rather than different technologies is needed where municipal wastewater systems apply water conservation measures to reduce the impacts on the ecological, socio-cultural and economic balance of the area applying the technology. The impact assessment of these solutions is of paramount importance as it aims to identify and quantify the most important resource use.

In an urban environment, water, often defined as the fundamental life sustaining substance, has an ever changing character; from raw water to drinking water, via households and industry to wastewater, which is further mixed with storm water, and groundwater, and finally treated to some degree and released to receiving water bodies. Therefore, the improvement in global health and sanitation and the consequent reduction in the spread of disease in urban areas depend largely on good hygiene practices, availability of health facilities, and reliable collection and treatment of wastewater (Muga and Mihelcic, 2008).

The El Salitre WWTP is one typical example of a centralized technological solutions which has been applied as a response to sanitation and the deterioration in the quality of the sub-catchment and improve the quality if the Bogotá River downstream as it crosses the Bogotá city, the sixth largest city in Latin America (Skinner, 2003) and which houses 30% of the Colombian manufacturing industry and 15% of the country’s population (Botero, 2005). What is the sustainability and adaptive capacity of urban WWTPs in the pursuit towards sustainability in an urban ecological system?

This research is of particular importance given that many of Colombia’s urban wastewater treatment plants have been evaluated to be in poor operating condition (Arias and Brown, 2009; Blackman, 2009) and as such contribute to the contamination of water bodies. In 2003, it was presented that of the twenty seven (27) WWTPs, sixteen (16) were waste stabilization ponds (WSPs), seven (7) were activated sludge systems, three (3) were anaerobic reactors, and one (1) was a sequencing batch reactor (CAR, 2003). Furthermore, the domestic rather than the industrial sector have been presented to be the leading contributor to water pollution as it contributed over three-quarters of the total biochemical oxygen demand (BOD) discharged from all point sources in 1999 (IDEAM, 2002a). The present rate of increase in the population of the Bogota city, with 87% urbanization around the upper basin of the Bogota River, and the consequent transformation of the Salitre watershed area (and the urban ecosystem hydrology) is creating environmental problems that threaten environmental, societal, and economic sustainability.

Environmental problem is understood here to mean the multiple and ripple effects that an alteration in ecological systems have on the environmental, technical (functional), economic and socio-cultural aspects respectively. The challenge, therefore, is to justify and link this need with the sustainability on the socio-ecological system of the savanna area and the treatment technology. In the light of this, the general objective of this research was:

- To evaluate the sustainability of conventional sewerage and domestic wastewater treatment system in Bogota by using the life cycle assessment approach (LCA) on sustainability development indicators (SDIs).

To achieve this aim, the below specific objectives were planted as a methodological approach:

- Review existing information on the selected conventional wastewater treatment system (WWTS) in the Bogota City.
- Identify the sustainable development indicators (SDIs) of the WWTS.
- Analyze the sustainability of the selected WWTP.
- Analyze how the SDIs can be improved through adaptation of management processes or technology.

The interaction of technology with the environment schematically represented by Balkema et al., 2002 (see **Figure 1**) shows that the demands of the end user are translated into functional criteria that must be fulfilled by the technology. According to Balkema et al., (2002) technology draws resources from its environment and affects this environment through contamination in order to fulfill is function. As a result, sustainable technology must not threaten the quantity and quality (including diversity) of the resources. As the quantity and quality of the resources and the resilience of the environment to emissions change over time and space, the most sustainable technological solution will change accordingly.

Understanding impact to mean the multiple and ripple effects that the function of any technological system has on the three dimensions of sustainability (environmental, economic and socio-cultural aspects of ecological systems), a set of ten (10) sustainable development indicators (SDIs) based of the four dimensions of the sustainability of an urban WWTS were developed to investigate the overall sustainability of the El Salitre WWTP: functional, environmental, economic and socio-cultural indicators. The system boundary was limited to the first-order and some second-order processes of the plant. The functional unit of each cubic meter of wastewater treated per day was used. Data was collected from the Bogota Water and Sewage Company (*Empresa de Acueducto y Alantarillado de Bogotá*, EAAB) database - the operators of the wastewater treatment plant, literature and public databases based on the indicator categories from the year 2004 to 2010.

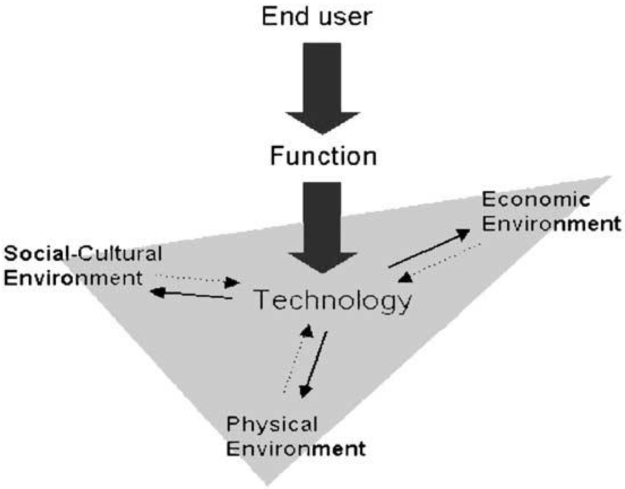


Figure 1: Technology interacting with the environment (Balkema et al., 2002)

The used data were obtained in accordance with the five identified environmental and technical systems of the life cycle of urban wastewater management processes: influent characteristics, treatment process of the influent, purchased electricity generation/chemicals, handling of by-products such as solids, biosolid, biogas and effluents and services which included maintenance (diesel fuel, lubricating oil, and lubricating tallow), packaging (biosolids disposed of in landfill) and transportation. Inventory results from the selected SDI criteria were used as basis to evaluate the plant's total impact from both the water and sludge treatment lines and as such enabling the identification of the stages where improvements were needed.

The functional indicators applied were effectiveness, efficiency, adaptability and flexibility and maintenance required, The environmental indicators used included effluent quality, sludge quality, global warming potential (GWP) from gaseous emissions, nuisance and public health risk. Total, operational, maintenance and energy costs per volume of wastewater treated and user cost were used as the economic indicators while aesthetics, public participation with regards to the stimulation of sustainable behavior by increasing the end-user's awareness, community participation evaluated by number of visits to the plant and expertise (level of education) were the socio-cultural indicators applied.

The study incorporated the life cycle method on the above mentioned SDIs with particular emphasis on sustainability, efficiency, overall performance and adaptability of the operational phase of the El Salitre watershed WWTP to provide answers to the research question. Life Cycle Assessment (LCA) methodology based on sustainable development indicators (SDI) was applied in this research not only because it is a standardized method designed to evaluate and where possible reduce the environmental impact for the entire life cycle of a product, process or service (Field and Ehrenfeld, 1999) but that it also provides opportunities for innovative processes and learning purposes for the much needed adaptability (NTC-ISO, 14040). SDIs were integrated to the method to overcome the limitation of LCA to identifying impacts tied only to the product function and not specifically to where the impacts occur, making it site-independent (Ness et al., 2007), use of large quantity of data which results in loss of insight into relevant emissions when data are aggregated into standardized environmental impact categories and restriction to a set of technical and environmental aspects only (Balkema et al., 2002).

Results obtained from the research clearly showed that the sustainability of a treatment technology, such as the El Salitre WWTP, is not process limited but an integration of the whole system boundaries of the system making it possible to compare a large variety of integral solutions. Target plot showed that the plant has a varying degree of sustainability and adaptation capacity in the 4 dimensions and indicators and as such improvements needs to be made. Improvements based on BMP principles were suggested and applied to adapt the treatment process and in effect provide alternatives to cushion the effect of the wide range of influent characteristics entering the treatment system.

The hypothesis of this study was that SDIs would provide the basis to compare the total impact among the various stages in both water and sludge treatment lines, enabling the identification of the stages to focus in order to find improvements in the overall performance of urban conventional treatment system. As such, another means of assessing improvement alternatives into the management of urban WWTPs for their overall sustainability which focuses on the impacts from identified stages was investigated.

2 THEORETICAL FRAMEWORK

2.1 SUSTAINABILITY AND SUSTAINABLE WASTEWATER MANAGEMENT CONCEPT

The most commonly cited definition of sustainable development (SD) is that from the World Commission on Environment and Development (WCED, 1987) which defines sustainable development as: ‘Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs’. As such sustainability strives for the maintenance of economic well-being, protection of the environment and optimum use of natural resources, and equitable social progress which recognizes the just needs of all individuals, communities, and the environment both today and in the future. Because of the dynamic nature of these components, sustainability needs to be understood as a direction rather than a static end goal giving room for the need to design human and industrial systems that ensure humankind’s use of natural resources and cycles do not lead to diminished quality of life due to either losses in future economic opportunities or adverse impacts on social conditions, human health and the environment (Mihelcic et al., 2003).

This need has led to the development and application of concepts such as the environmental sustainability of development, urban sustainability, and sustainable urban development and by extension sustainable wastewater management (SWWM) with regards to the application of engineering solutions. It is important to note that, although the concept of sustainability was defined in the 1980’s it was not until 1992, after the UN conference on Environment and Development in Rio de Janeiro did the concept become globally recognized among the 180 participating countries. This brought to bear the complex interaction between natural and human systems and their responses to human induced impacts which presents difficulties when one tries to quantify sustainability due to its multi-dimensional nature.

In the light of the multi-dimensional character of sustainability three dimensions can be defined economic, environmental, and social–cultural which has been incorporated into sustainable wastewater management (SWWM) concept by Muga and Mihelcic (2008) in their study (see Figure 1). Therefore, sustainability concept offers a range of alternatives of how to attain a sustainable wastewater management, from improving the existing technology to substitution with a more sustainable technology. However, the attainability of sustainable urban wastewater management has been questioned. This question has been highly argued in literature and strategies well elaborated. One such strategy was the one presented by Anggraini (2007) which include: sufficient environmental protection by reducing the emission of pollutant to maintain the quality and the diversity of ecosystem, wastewater and sewerage management must provide at least the minimum service to the community and low or no health risk of infectious disease or any toxic matter. Kärrman (2001), on the other hand, suggested four approaches towards SWWM which include the separation of nutrient-rich flows from other waste flows, reducing pressure on scarce freshwater resources by maximizing reuse opportunities, prevention contamination of wastewater flows and the disposal of unavoidable pollution on landfills. Another strategy against unsustainable urban watershed management was presented by Bultler and Prakinson (1997) which includes the reduction of inappropriate “use” of potable water as a carriage medium in sewers.

As such, current urban wastewater management, characterized by a centralized, end-of-pipe-treatment, long-lived infrastructure, dilution of wastewater streams containing pathogens and toxic compounds such as heavy metals and organic micro-pollutants which makes recovering of the different resources such as water, energy and space difficult (Balkema et al., 2002; Panebianco and Pahl-Wostl, 2006; Etnier et al, 2007) can be perceived to be unsustainable. Therefore, in the words of Kärrman (2001), “there is still a challenge to make the sustainability concept useful for concrete decision-making” as engineering and action plans should consider preventive actions during all human activities, on-site treatment and reuse close to production, off-site treatment and reuse, on-site or off-site concentration and storage, treatment at small-scale treatment plants using novel and low-tech technology.

2.2 SUSTAINABLE WASTEWATER TREATMENT TECHNOLOGY

Sustainable technology is described, in this study, as technology that is compatible with or readily adaptable to the natural, economic, technical, and social environment and that offers a possibility for further development over a long-term and global view. In analyzing, therefore, the sustainability of technology the different dimensions should be taken into account. To avoid transfer of the problem over time or space, the technological solution should be based on a long and global view. Realizing that the solution is embedded in a complex entirety, an integrated solution then becomes a plausible aim. Furthermore, a diversity of sustainable solutions must be available for different situations, preferably flexible as to adapt to future changes. This is particularly true given that different WWTP options differ in their performance characteristics and direct impacts on the environment. If one of the main functions of wastewater treatment systems is to minimize the impact on the environment, then they should be designed accordingly (Pasqualino et al., 2009).

The interaction of the technology with the environment was schematically represented earlier by Balkema et al., (2002) as shown in **Figure 1** where the demands of the end user are translated into functional criteria that must be fulfilled by the technology. According to Balkema et al., (2002): “in order to fulfill its function the technology draws from resources in its environment and affects this environment through contamination”. Sustainable technology is technology that does not threaten the quantity and quality (including diversity) of the resources. As the quantity and quality of the resources and the resilience of the environment to emissions change over time and space, the most sustainable technological solution will change accordingly. The science of assessing the sustainability of technology is fast becoming of huge importance as a tool that provides decision-makers with an evaluation of global to local integrated nature–society systems in short and long term perspectives in order to assist them to determine which actions should or should not be taken in an attempt to make society sustainable (Ness et al., 2007).

However, Donnelly and Boyle (2004) argued that limiting the assessment of impacts (in this case the impact generated by urban wastewater systems) only to environmental, social and economic impacts is restrictive if the real sustainable issues are to be evaluated. Some of the setbacks they identified from these approaches were:

- Significant focus on only negative social, environmental and economic impacts.
- Inability to integrate the assessment of systems across the environmental, economic, social, cultural dimensions of development despite their attempt to assess impacts these multiple dimensions
- Inadequate integration of sustainability assessment practices with project development and decision-making processes as they are frequently done to comply with regulations.
- Difficulty with the use of quantitative indicators for sustainability assessment, as these over-simplify the responses and interactions of highly complex human and natural systems, and their inability to handle the complexities, uncertainties and indeterminacies associated with the functioning of those systems, the confusion that can result from the attachment of multiple different values and interpretations to the same indicator , the lack of relevance of chosen indicators to the needs of decision-makers and the difficulties in measuring qualitative information such as community values and feelings
- Lack provision for the inclusion of fundamental sustainability principles, particularly the application of the Precautionary Principle.

As such, extensive, coordinated, integrated, multi-disciplinary and context specific planning approaches are required at the regional level to identify threats and risks to the sustainability of critical systems and processes, and paths of action to address them.

2.3 CONVENTIONAL MUNICIPAL WASTEWATER TREATMENT SYSTEM

2.3.1 NATURE AND CHARACTERISTICS OF URBAN WASTEWATER

Domestic wastewater is the spent water originating from all aspects of human sanitary water usage constituting a combination of flows from the kitchen, bathroom and laundry originating from residences, commercial and institutional establishments. Raw or untreated sewage is mostly pure water as it has been described to comprise about 99.9 % water and 0.1% impurities. Most of these impurities are biodegradable organic material and pathogenic microorganism (Boari et al, 1997).

The principal physico-chemical and biological characteristics of the pollution load of wastewater are temperature, solid content, organic matter, inorganic compounds and metals, gases and volatile compounds, taste and odor, color and pathogenic organisms. The solids content of a typical urban wastewater may be physically classified approximately as shown in **Table 1**. In a typical urban wastewater, about 75 percent of the suspended solids and more than 50 percent of the filterable solids are organic in nature (Metcalf and Eddy, 1991).

Organic compounds are normally constituted of a combination of carbon, hydrogen and oxygen, together with nitrogen in some cases. Other important elements, such as sulfur, phosphorus and iron, may also be present. The presence of quantities of nitrate and phosphorus in domestic sewage is due to human metabolic processes and, for phosphorus in particular, to the use of detergents. **Table 2** shows the different forms of nitrates found in urban sewage. The inorganic ammoniacal fraction is quickly and totally biodegradable, while the organic fraction is approximately 15%. In general urban sewage contains all forms of phosphorus, while after biological treatment normally only ortho-phosphates are detectable. If sewage is to be reclaimed and used again it is recommended to analyze for the presence of pathogenic organisms. The enteric, organisms present in sewage include viruses, bacteria, protozoa and helminthes.

Table 1: The approximate solids content of an urban wastewater (Boari et al, 1997)

Solids	Suspended 30.5%	Settleable – 22.2%
		Non settleable – 8.4%
	Filterable 69.5%	Colloidal – 6.9%
		Dissolved – 62.5%

Table 2: Various forms of nitrogen in urban wastewater (adapted from Boari et al, 1997)

Total Nitrogen	Organic nitrogen	Non biodegradable, soluble, ≈ 3%
		Non biodegradable, particulate, ≈ 10%
		Biodegradable, ≈ 12%
	Inorganic nitrogen, ≈ 75%	

Generally, the nature and characteristics of urban wastewater is subject to environmental variations identified by Leitao et al., (2005) in their review of the effects of operational and environmental variations on anaerobic wastewater treatment systems to include:

- Variable sewage production over the day resulting from the cyclical nature of human activities particularly for municipal wastewater.

- Wrong connections characteristic of separated sewer system leading to significant overloads in networks as well as in treatment plants runoff water and rainfall contributions.
- First-flux phenomena typical of combined sewer networks in cases where storm water contributions result in increased suspended solids (SS) and chemical oxygen demand (COD) concentration in the first minutes of the event.
- Dramatic population increase during holidays lead to high flow rate variations over the year.
- Operational procedures at treatment plant can result in increased hydraulic and organic loads, for example stopping one anaerobic unit for maintenance implies the others have to cope with the entire flow rate.
- Several types of disturbances can manifest in case of industrial wastewater, even under normal operational conditions, given that the flow rate and waste concentration vary with the industrial processes routine.

2.3.2 CONVENTIONAL WASTEWATER TREATMENT SYSTEMS

Municipal wastewater can be treated in a number of different ways although each option for wastewater treatment has different performance characteristics and also different direct impacts on the environment. Some systems are energy intensive, some materials intensive requiring high embodied energy while others occupy a lot 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 of discharging untreated water into natural water system is minimized (Pasqualino et al., 2009) alongside impacts to the ecosystem as a whole.

Boari et al., (1997) classified water treatment systems into two: natural water treatment systems and urban wastewater treatment systems. The former, also known as ecological treatment methods are generally decentralized systems most of which make use of natural purification processes that happen in the zones of interaction between water and soil or plants. Any flow that is treated in them undergoes primary treatment, usually screening and settlement (Burkhard et al., 2000). Some examples of ecological treatment methods include Constructed and natural wetlands (Kivaisi, 2001; Siracusa and La Rosa, 2006; Vymazal, 2007, Arias and Brown, 2009) living machines (Neralla et al., 2000; Kavanagh and Keller, 2007; Lansing and Martin, 2006; Ye and Yi, 2009), aquaculture (Guterstam et al., 1998; Costa-Pierce, B, 1998), and sand filters. Boari et al (1997) identified the objectives of the latter as:

- To confer and preserve the inherent physical chemical and biological qualities of water of different origins which make it suitable for specific uses such as water for drinking and for use in productive processes;
- To permit wastewater treatment which will protect the public from health risks without causing any damage to the environment;
- To confer and preserve those characteristics of water in its natural environment which are necessary for the conservation and development of ichthyo fauna and aquatic vegetation, and
- To provide a drinking water source for cattle and wild animals or for recreational and aesthetic purposes.

On the other hand, Burkhard et al., (2000) reviewed and evaluated the potential of several technologies to treat urban domestic wastewater and grouped the available conventional techniques into different treatments approaches: centralized conventional sewage treatment systems and decentralized conventional systems.

Centralized conventional sewage treatment works consist of several stages, of which the primary and secondary stages are the bare minimum and focus nowadays. Depending on whether there are risks of eutrophication, presence of toxic substances or sensitivity risk from discharge to the environment, the tertiary stages is applied. As described earlier, conventional treatment systems produce considerable amounts of sludge and they are generally very energy consuming.

The problem associated with these treatment technologies is their lack of sustainability as these systems flush pathogenic bacteria out of the residential area, using large amounts of water and often combines the domestic wastewater with rainwater, causing the flow of large volumes of pathogenic wastewater. In fact, the conventional sanitary system transfers a concentrated domestic health problem into a diffuse health problem for the entire settlement and/or region. In turn, the wastewater must be treated where the cost of treatment increases as the flow increases. The abuse of water use for diluting human excreta and transporting them out of the settlement is increasingly questioned and being considered unsustainable. (Bdour et al., 2009)

Centralized conventional systems are listed below without any explanation because these techniques are widely known (see, for example, Metcalf and Eddy, 1991; Boari et al., 1997) and **Table 3** shows the most commonly used treatment system.

- Activated sludge process (AS) or one of its many modifications is most often used for larger installations and involves process such as tapered aeration process; modified aeration process; continuous-flow stirred tank; step aeration process; contact stabilization process; extended aeration process; oxidation ditch; carrousel system; high-rate aeration process.
- Percolating filters (PF) or trickling filters applied in some cases for large installations.
- Rotating biological contactors (RBC).
- Oxidation ponds (OP) (stabilization ponds or aerated lagoons, anaerobic ponds, and facultative ponds.

Furthermore, the treatment consideration of urban wastewater is the processing of solids generated and use or disposal of biosolids since these systems are always designed to produce two products: clean water that can be reused or released into the environment, and biosolids. This is particularly important because in actual urban water systems much of the nutrients in wastewater have about 95 % of the phosphorus (P) and 20 % of the nitrogen (N) trapped in sewage sludge. According to Pasqualino et al., (2009) the P and N sludge content allows for the equivalent N and P nutrients used as mineral fertilizer or for land reclamation and land restoration purposes thereby reduces the need for mineral fertilizers.

Table 3: Selected Pollutants and Associated Pretreatment Processes (Boari et al., 1997)

Pollutant	Pretreatment Processes	Pollutant	Pretreatment Processes
Bio-Chemical Oxygen Demand (BOD)	Activated Sludge (AS) Trickling filter Aerated lagoon Oxidation ditch	**Heavy metals**	Biological treatment Chemical precipitation Evaporation Membrane process
Total Suspended Solids (TSS)	Sedimentation Screening Flotation Chemical precipitation	**Fats, Oil and Grease (FOG)**	Coagulation Flotation Biological treatment Membrane process
Nitrogen	Nitrification/denitrification Air stripping Breakpoint chlorination	**Volatile Organic Compounds**	Air stripping Biological treatment Carbon adsorption
Phosphorus	Chemical precipitation Biological treatment Air stripping	**Pathogens**	Chemical disinfection UV radiation

On the other hand, decentralized conventional systems are used for one or a few remote houses. Some of the methods have been abandoned, as they can be a threat to ground or surface water. This is especially true for the non-biological groups. They are however, mentioned in this study because of their possible use as cost-effective pre-treatment methods for decentralized treatment.

- Non-biological treatment (NB) which includes processes such as cesspools, septic tanks, and settlement tanks all of which has been extensively descried in literature (Metcalf and Eddy, 1991; Al-Shayah and Mahmoud, 2008; Gill et al., 2009).

- Package biological plants (PB) such as recirculating biological filter (RBF), activated sludge package plants or sequence batch reactors (SBR), leach fields (LF).

2.4 ASSESSMENT OF THE SUSTAINABILITY OF URBAN WASTEWATER SYSTEMS

The sustainability of wastewater treatment systems can be accessed through different assessment tools such as environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle assessment (LCA), positional analysis (PA), cost-benefit analysis (CBA), material intensity per unit service (MIPS) analysis, total material requirement (TMR) analysis, ecological footprint (EF), exergy analysis, system analysis, and emergy analysis.

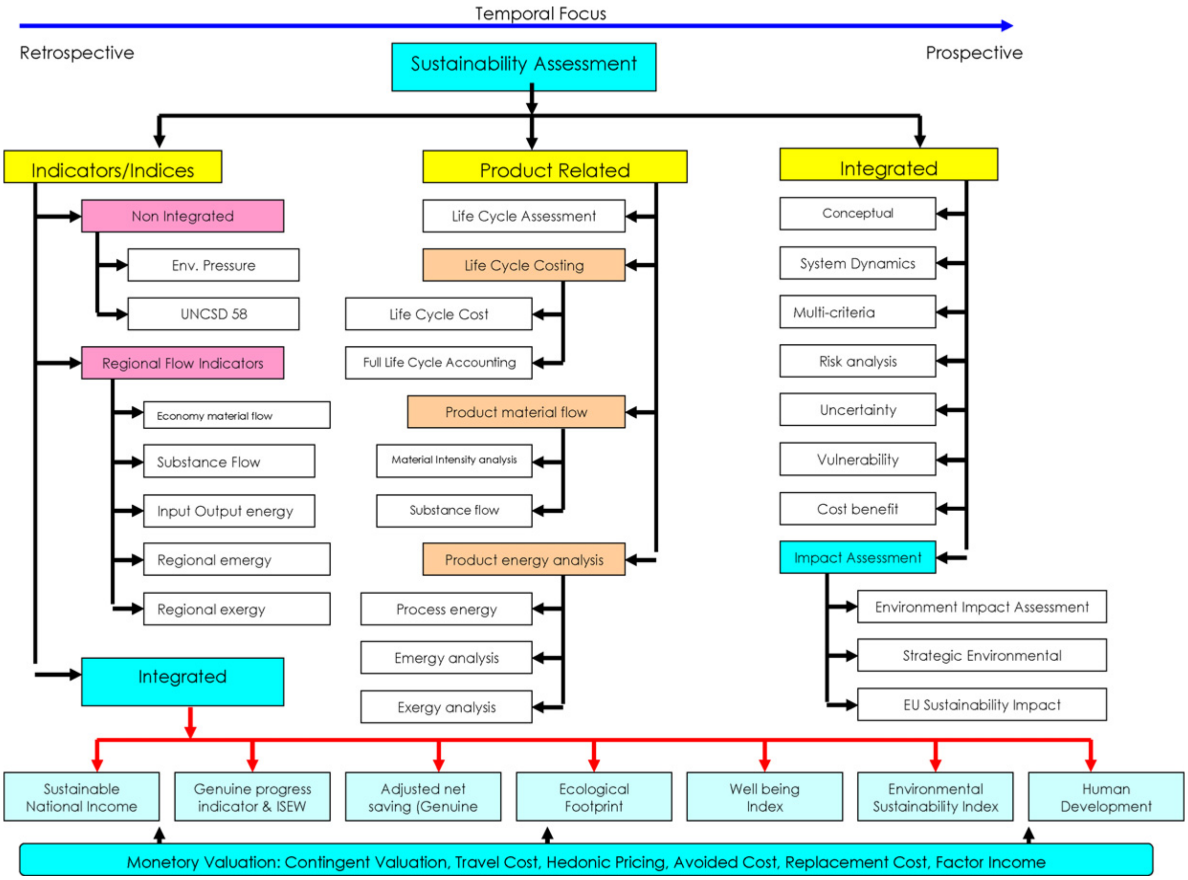


Figure 2: Framework of Sustainability Assessment Tools. (Ness et al., 2007)

Two widely accepted classification of these methods was mentioned by Anggraini (2007) to include single indicator approach for instance through exergy analysis or economic analysis and multiple indicator approach, such as LCA and system analysis respectively (see **Figure 2**). The most commonly used, however, are exergy analysis, economic analysis, and LCA and the EIA in the case of most developing countries such as Colombia (see Ortiz-Rodríguez, et al., 2010; Singh et al., 2009). Only four tools out of all the above mentioned methodologies and their application in assessing the sustainability of the wastewater treatment and highlighting the reason for the use of the LCA approach in this study are analyzed.

2.4.1 EXERGY ANALYSIS

This sustainability evaluation method enjoys the advantage of using only a single unambiguously quantifiable indicator, referred to as exergy with no weighting required (Balkema et al., 2002). Exergy is the useful part of the energy that part that can perform mechanical work and can be defined as that part of the energy that is convertible into all forms of energy. Balkema et al., (2002) stressed that the one limiting factor in the application of this approach is that it gives insight into the efficiency of the processes as the more exergy efficient alternative but not into the different environmental impacts while Moberg (1999) presented that it does not include toxicological and biodiversity aspects. As such, it is used mainly for decision-support and learning that prospectively estimates the efficiency of potential developments and retrospectively presents potential beneficiary changes (Moberg, 1999).

Hellström (1998) concluded that the urine separation system is a more favorable option when he used exergy to compare the importance of nitrogen removal, a centralized wastewater treatment plant with a decentralized system incorporating urine separation. The study also found that there is close relationship between exergy flows to the handling of organic matter, thereby making the possibility to retain exergy through the production of methane (Balkema et al., 2002).

2.4.2 ECONOMIC ANALYSIS

This is another single indicator based assessment which evaluates the wastewater treatment systems based on economic theory is that sustainability could easily be integrated into decision-making if expressed in terms of money. Tools such as: cost-benefit analysis, life cycle costing, and total cost assessment, all balance the expected costs and benefits, and are often the first step in a project. In theory, all kinds of costs and benefits can be included, however in practice these tools are mostly used as a one-dimensional technique incorporating only financial costs and benefits. The obvious reason is that most social and environmental costs are difficult to quantify (Balkema et al., 2002).

Balkema et al., (2002) in their review recognized the importance of this tool to translate environmental and socio-cultural indicators into monetary values which is a part of the decision-making process since it includes normative choices such as fixing values and weighting factors of different indicators. In a perfect market-economy, prices would reflect the value of things as perceived by society. However, no perfect market economy exists and especially in the water sector prices are regulated by governmental organizations with taxes and subsidies. As such, an in-depth economic analysis of the sustainability of water supply and wastewater treatment could provide a valuable insight in the ‘real’ cost of water services.

2.4.3 ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

This is a multiple indicator tool developed to get environmental aspects as a prospective method to foresee impacts and to provide strategic decision support resulting from the examination, analysis and assessment of planned activities with a view to ensuring environmentally sound and sustainable development (Toro et al., 2009; Moberg, 1999). Therefore, it supports government and other authorities in decisions concerning permits for proposed projects and support authorities in town planning and comprehensive municipal planning. Wood (2003) states that, in principle, “the boundaries are defined by the distribution (spatial and temporal) of important direct and indirect impacts caused by the proposed project” (Moberg, 1999).

While EIA does not need a reference object there is, however, a requirement that EIA should consider alternatives to the proposed project localization (exceptions can be made) and design, including the zero alternative describing what will happen if the project is not carried out. This implies a degree of comparison is required.

In Colombia the purpose of an EIA is to identify and describe all the possible alterations, direct and indirect impacts, of the development on the biotic (humans, animals, vegetation), abiotic (ground, water, air, climate, landscape) and cultural and socioeconomic environment, as well as resource management (MAVT, Degree 1220, 2005). This would in theory mean that all environmental burdens should be considered. In practice, this is probably not be the case as Toro et al. (2009) demonstrated in their study that the deficiencies in the application of EIA is “adversely affecting the environment, which should be protected because of its fragility, biological richness and high number of endemic species”. Lack of testing against what really happens (even though monitoring is part of the suggested performance) limits the potential for improvements of the method (Moberg, 1999) and does provided much adaptive learning opportunities. Also, EIA-performers often rely on too weak data to reduce cost.

2.4.4 LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment (LCA) is the most established and well-developed product-related assessment tool (Ness et al., 2007). It is a standardized method developed to assess different environmental impacts encountered during a product's lifetime from extraction of raw material, energy use and waste release, as well as all associated transports (ISO 14040, 1997; SIAC, 2006; NTC-ISO, 2007) **a**s such giving it an edge over the EIA method. It has been defined as "an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements" (Barton et al., 1999). It helps decision-makers select the product or process that result in the least impact to the environment. LCA data identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase). If an LCA were not performed, the transfer might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product selection processes (SIAC, 2006) such as EIA. Moberg (1999) argued that the focus of the assessment is not the product itself but rather the function of it used for internal learning purposes and communication of environmental aspects of products. As UNEP (1996) explains it "the aim of LCA is to suggest more sustainable forms of production and consumption".

LCA, according to the Colombian Technical Standard ISO 14040, can help to:

- Identify opportunities to improve the environmental performance of products at different stages of their life cycle.
- Provide information to decision makers in industry, government or nongovernmental organizations (e.g., strategic planning, priority setting, design and redesign of products or processes).

- the selection of relevant environmental performance indicators, including measurement techniques, and
- Marketing (e.g., implementing an environmental labeling scheme, developing an environmental claim, or an environmental product declaration).

As can be observed from **Figure 3**, LCA is a structured methodology starting with defining the goal and scope of the study. Thereafter, a life cycle inventory of environmental aspects is made which provides a fingerprint for the defined activity by quantifying the mass of raw materials and consumption of energy. This encompasses the extraction from the earth of all raw materials used both directly by the activity and indirectly through provision of raw materials used to supply energy and finished/semi-finished products demanded by the system. It includes emissions to air, discharges to water and generation of solid waste. Essentially the system under consideration should mass balance with inputs from the environment with discharges to the environment.

Finally, these environmental aspects are categorized in environmental impact categories, such as depletion of resources, global warming potential, ozone depletion, acidification, ecotoxicity, desiccation, eutrophication, landscape degradation, etc. followed by improvement analysis. These categories can be normalized and weighted to come to a final decision whether to choose one technology or the other. The advantage of LCA is that it is a well-described and standardized structure applicable to a wide range of products and services including the different parts of the urban water cycle (Balkema et al., 2002; *Barton et al., 1999*) incorporating an adaptive learning process that the EIA does not consider.

The one limitation of the assessment of a complete life cycle is that it requires a large quantity of data. Aggregation of the data into the standardized environmental impact categories means loss of insight into the emissions that are of particular relevance to wastewater treatment. Furthermore, additional indicators are needed to measure sustainability as LCA limits itself to a restricted set of technical and environmental aspects (Balkema et al., 2002). These notwithstanding, LCA have been applied successfully to evaluate various wastewater treatment systems (see Lundin and Morrison, 2002; Lassaux and Germain, 2000).

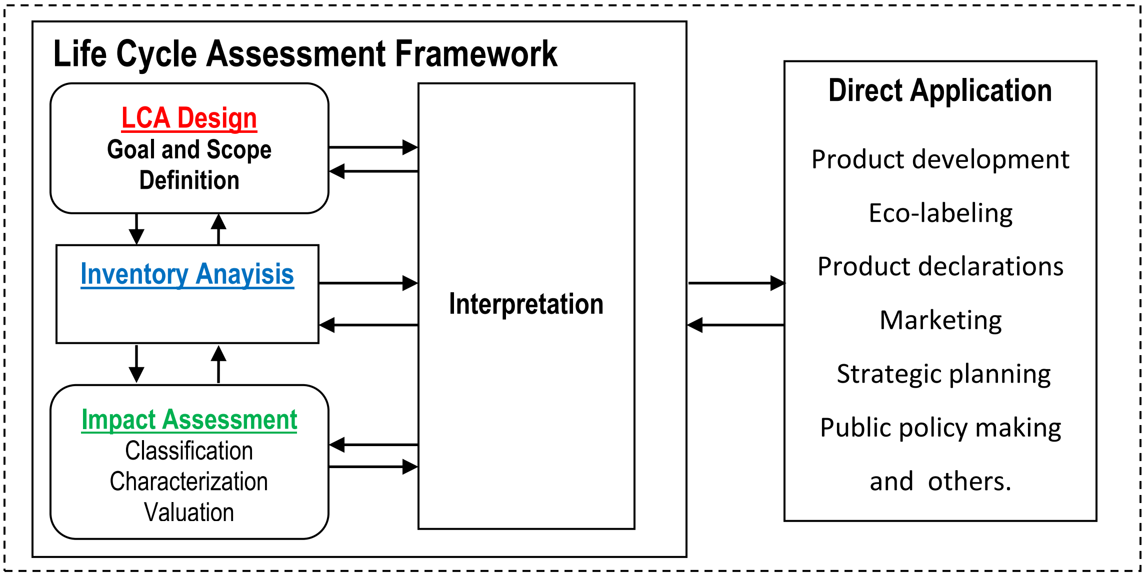


Figure 3: Life Cycle Assessment Framework (Chaosakul, 2005).

2.5 INDICATORS FOR SUSTAINABLE ASSESSMENT OF WASTEWATER TREATMENT SYSTEMS

Indicators are pieces of information, which have a wider significance than their immediate meaning and used as synthetic and representative reflection of a greater, more complex sum of phenomena. They serve the overall purpose of quantifying trends in observable phenomena and are often characterized as signs or signals that relay a complex message from potentially numerous sources in a simple and useful manner. An indicator, therefore, aids decision-making, simplifies or summarizes important properties, visualizes phenomena of interest and quantifies and communicates relevant information that provides early warning for the prevention of environmental, social and economic impacts. Therefore, a sustainability assessment indicator will not limit itself to a process but will rather be an integrated assessment over a whole chain of processes that provide a certain service and according to Singh et al., (2009) needs to be compared to a reference value such as thresholds for it to be used in decision-making processes.

Defining sustainability indicators is the last important step, as the selection of sustainable solutions is based on these indicators. A sustainable solution means limited use and limited degradation of resources through harmful emissions, at the same time avoiding the export of the problem in time or space. Sustainable development indicator (SDI) was used for this study as it has been extensively applied to various urban water system studies (Anggraini, 2007; Lundin, 1999). A plethora frameworks sustainable development indicator (SDI) selection exists including the causal chain or stress-response model such as the Pressure-State-Response (PSR) model developed by the Organization for Economic Co-Operation and Development (OECD, 1998), The Driving Force Pressure State Impact Response (DPSIR) model which is an extension of the PSR framework and the State-Pressure-Management developed by Vega (2005). The PSR framework based on the concept of causality: human activities exert 'pressures' on the environment and change its quality and the quantity of natural resources (the 'state'). Society responds to these changes through environmental, general economic and sectored policies (the 'societal response'). The latter forms a feedback loop to pressures through human activities (Singh et al., 2009).

The sustainability indicator framework for the evaluation of governmental progress towards sustainable development goals was developed by the United Nations Commission on Sustainable Development (UNCSD, 1995) took into account the four dimensions of sustainable development (social, economic, environmental and institutional). However, another type of approach used - the life cycle assessment framework - focuses on societal activities and as such tends to provide a link between these activities to impacts on the environment through an evaluation or aggregation method (Lundin and Morrison, 2002). The Life Cycle Assessment framework, although similar, has the advantage of including all significant impacts or benefits on the environment that occurs throughout the life cycle and relates these to a functional unit such as per person and year.

However, regardless of the frameworks, indicators should be (i) based on a sound scientific basis and widely acknowledged by scientific community; (ii) transparent, e.g. their selection, calculation and meaning must be obvious even to non-experts; (iii) relevant, e.g. they must cover crucial aspects of sustainable development; (iv) quantifiable, e.g. they should be based on existing data and/or data that is easy to gather and to update; and (v) limited in number according to their purposes they are being used for (Lundin and Morrison, 2002). In the light of these criteria and considering the aim of using indicators to indicate the sustainability of development projects, SDIs as presented by Palme (2010) and Singh et al. (2009) can be summarized to serve the following functions:

- Depict current conditions, anticipate and assess conditions and trends, evaluate various management actions for the future.
- Provide warning of impending changes to prevent economic, social and environmental damage.
- Aid planning by the formulation of strategies and communication of ideas,
- Contribute to learning, structuring understanding, and conceptualization, and
- Expand, correct, and integrate worldviews.

There exist various criteria or characteristics for desirable sustainability indicators. Lundin and Morrison (2002) presented that the process of selection of indicators have been dealt with by few studies. They went ahead to mention the PICABUE theoretical approach of Mitchell (1997) and the Bellagio principle presented by Hardi and Zdan (1997). Singh et al., (2009) presented The Wuppertal Institute criteria for indicators selection based on the four dimensions of sustainable development, together with inter-linkage indicators between these dimensions (See **Figure 4**). The latter aims to serve as guidelines for sustainability assessment process including the choice and design of indicators, their interpretation and the communication of results. Life cycle assessment (LCA) is another alternative approach widely applied in industry, to evaluate and reduce environmental impacts for the entire life cycle of a product, process or service from its origin to its final destination.

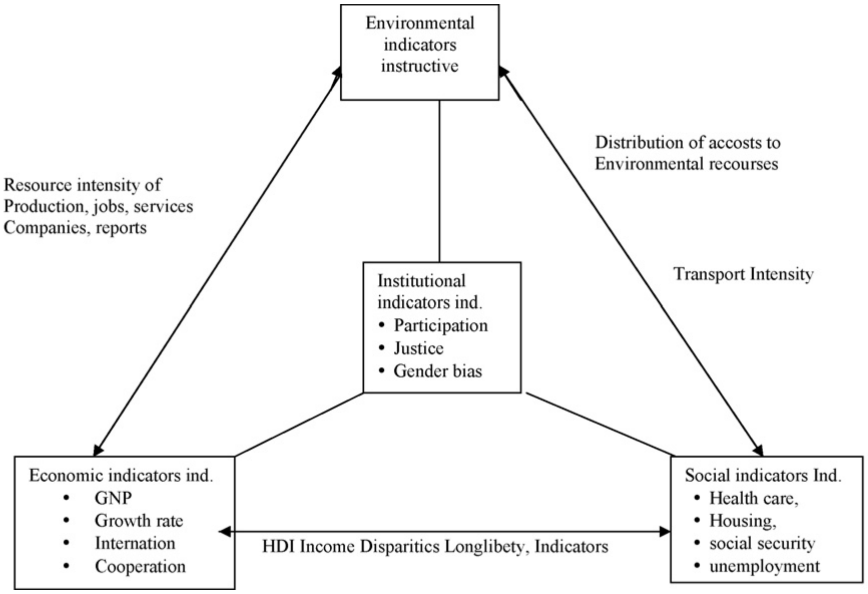


Figure 4: The Wuppertal Sustainable Development Indicator Framework (Singh et al., 2009).

As described earlier (see figure 1), it is possible to distinguish three types of resources: economic, environmental and socio-cultural. Balkema et al., (2002) presented that while the economic, environmental, and social–cultural indicators give insight into the efficiency of the solution, the functional indicators determine the effectiveness of the solution. The same categorization was employed in the selection of the indicators including one additional category, namely the functional indicators. Sustainability indicators used in literature differ and are presented in **Table 4.**

2.5.1 FUNCTIONAL INDICATORS

Functional indicators, also known as technical indicators, define the minimal technical requirements of the solution. For instance, for wastewater treatment this may be the minimal required effluent quality. Additional indicators may be adaptability (possibility to extend the system in capacity, or with additional treatment), durability (lifetime), robustness (ability to cope with fluctuations in the influent), maintenance required, and reliability (sensitivity of the system to malfunctioning of equipment and instrumentation) (Chaosakul, 2005).

2.5.2 ENVIRONMETAL INDICATORS

According to Chaosakul (2005) there is relative consensus on the environmental indicators, known also as environmental sustainability indicators (ESI). As mentioned by Lundin and Morrison (2002), this indicator has been applied in the evaluation of cities, regions or counties and in the environmental performance assessment of infrastructure, agriculture and production. They have the advantage of not just measuring environmental performance but take into account adjoining technical systems. Optimal resource utilization is used as an indicator, particularly addressing water, nutrients, and energy. In addition required land area, land fertility, and biodiversity are mentioned in several studies. Another group of environmental indicators is emission oriented, for instance the quality of effluent and sludge, combined sewer overflows, and gaseous emissions (see Balkema et al., 2002; Lundin and Morrison, 2002).

2.5.3 ECONOMIC INDICATORS

Economic indicators are decisive when choosing a technology in a practical situation. This is true when considering the process involved when the choice was to be made on the Bogota River (Botero, 2005). Commonly used indicators are costs of investment, operation, maintenance and labor requirements respectively (Chaosakul, 2005).

2.5.4 SOCIO-CULTURAL INDICATORS

Both social and cultural indicators are quite difficult to quantify and are therefore often not evaluated. However, their role in the implementation of technology is widely (Chaosakul, 2005; Balkema et al., 2002; Lundin and Morrison, 2002: Field and Ehrenfeld, 1999). Chaosakul, (2005) described indicators in this category to include:

- *Institutional requirements*: This refers to the various regulatory and control mechanisms used with respect to the management of wastewater treatment systems. These requirements should fit in the existing institutional infrastructure of the country or region.
- *Acceptance:* In different cultures, people will have a different perception of waste and sanitation, resulting in different habits. New sanitation concepts, including different toilet systems, may encounter social–cultural difficulties in the implementation. For instance: the need to explain to visitors how to use the separation toilet was one of the reasons to remove these toilets from the houses of an ecological village.
- *Expertise:* The selected technological solution requires a certain level of expertise for installation and operation. If the expertise is not locally available it may be gained through import or training.
- *Stimulation of sustainable behaviour:* Sustainable behaviour can be stimulated by tailoring the technological design such that sustainable behaviour is the most convenient option. Other ways to stimulate sustainable behaviour are increasing the end-user's awareness, participation, and responsibility.

Table 4: Overview of indicators in the sustainability indicators/criterion point of views to compare wastewater treatment systems (Adapted from Chaosakul, 2005).

Reference	Economic Indicators	Environmental Indicators	Functional Indicators	Socio-cultural indicators
Bultler and Parkinson (1997)	-	Water Nutrients Energy Pathogen removal/ health Pollution Prevention	Durability Flexibility/ adaptability Small scale/ onsite/ local solution	Local development
Balkema (1996)	Cost	Biodiversity/ land fertility Integration in natural cycles Optimal resource utilization Water Nutrients Energy Raw materials Pathogen removal/ health Pollution Prevention BOD/COD Heavy metals Sludge/ waste production Use of chemicals	Durability Flexibility/ adaptability Reliability/ security	Awareness/ participation Competence/ information requirements Cultural acceptance Institutional requirements
Hellstom et al. (2002)	Cost Labour	Land area required/ space Water Nutrients Energy Raw materials Pathogen removal/ health BOD/COD Heavy metals	Endure shock loads/ seasonal effects Flexibility/ adaptability	Awareness/ participation Cultural acceptance
Lundin et al. (1999)	-	Water Nutrients Energy BOD/COD Sludge/ waste production Use of chemicals	-	-
Lundin et al. (2000)		Chemical Use Electricity use Discharge of BOD, P and N in water Energy recovery Recycling of N and P	-	-
Mels et al. (1999)	Cost	Land area required/ space Energy BOD/COD Sludge/ waste production Use of chemicals	-	-

2.6 APPLICATION OF SUSTAINABLE INDICATORS ON URBAN WASTEWATER SYSTEMS

Sustainability Indicators has been used to evaluate urban wastewater systems in various countries both at small and large scales. Morrison et al., (2001) in their study of urban water system in King William's Town, a medium-sized city in the semi-arid, mostly underdeveloped Eastern Cape of South Africa applied 20 SDIs to evaluate the sustainability of the urban water system, and to evaluate the individual factors. At the end of the study the presented that only 15 SDI indicator criteria was found useful for the study area and was produced for use also in future studies. The study showed that some indicator criteria like raw water withdrawal, drinking water consumption, chemical use, wastewater production, treatment performance, loads to receiving, recycling of nutrients, assess to drinking water, sanitation and economic indicator were easy to apply in the study area as data were readily available. Other SDIs, like drinking water quality, energy use, and quality of sludge were difficult to apply because data were not readily available.

Lundin and Morrison (2002) only applied life cycle assessment (LCA), method of selecting environmental sustainable indicators (ESI) to present a procedure for assessing the environmental sustainability of urban water systems by investigating how the urban water systems had changed over time. They studied two cities: the urban water system in Göteborg, the second largest municipality in Sweden with approximately 450,000 inhabitants situated on the west coast of Sweden with an area of 450 km^2 and the city of King William's Town (KWT) and the previously independent municipalities of Breidbach and Ginsberg, with a total population of 35,500. The evaluation was carried out on four environmental and technical systems following the life cycle of urban water management: (1) withdrawal of freshwater, (2) production, distribution and use of drinking water, (3) collection and treatment of wastewater, (4) handling of by-products such as sludge, biogas and heat. They concluded from the study that LCA helped to determine priorities and with extended boundaries helped to identify ESI, which were not obvious such as recycling of nutrients and recovery of energy.

Life cycle assessment (LCA) methodology is used to evaluate the environmental profile of a product or process from its origin to its final destination. Pasqualino et al., (2009) used LCA to evaluate and identify improvement alternatives of a wastewater treatment plant. They found out that the highest environmental impacts in modern WWTP are caused by the stages of the plant with the highest energy consumption, the use of biogas from anaerobic digestion (95% burned in torch) and the final destination of the sludge (98.6% for agricultural use and 1.4% for compost). They presented that using biogas to produce electricity or a combination of electricity and heat provided the best environmental options since the energy produced would be enough to supply all the stages of the plant, thus reducing their environmental impact. With respect to biosolid handling, the best environmental option for the final destination of the sludge is to combine fertilizer replacement with use of the sludge in a cement plant (as a replacement for fuel and raw material).

2.7 URBAN WASTEWATER MANAGEMENT AND POLICY IN COLOMBIA

2.7.1 URBAN WASTEWATER PROBLEM

It is a general consensus that many of Colombia's water basins are severely polluted and the Bogota River basin, assigned a vulnerability index of 4.0 (from 2 to 7 range) with respect to its biophysical conditions and the human pressures exerted on it, is not an exception (Blackman et al., 2006). Domestic wastewater management in urban and semi-urban areas is based on the conventional approach of collecting the wastewater in traditional drainage systems and transferring it to a treatment plant. However, a variety of decentralized methods exist, which are being used in both rural and suburban areas. Decentralized and also ecological methods generally provide simple, low-cost and low maintenance methods of treating domestic wastewater in small towns.

The urban drainage system in the Bogota city, however, consists of combined and separated systems, characterized with huge numbers of wrong connections where the total generation of wastewater is approximately 10 cubic meters per second, 15% of the total national generation. Domestic and industrial wastewater and combined sewer overflows are discharged untreated into three urban rivers (Salitre, Fucha and Tunjuelo) and other open channels across the city. The dry weather wastewater flow is put at about 17 m^3s^{-1} while the capacity of the wastewater system (the primary treatment plant at Salitre) is 4 m^3s^{-1}. The effect on the Bogota River as presented by Rodriguez et al. (2008), the receiving main stream with a mean upstream flow of 10 m^3s^{-1}, is the anaerobic condition that stretches to about 60 km. Considering this, the Bogotá River is one of the most polluted rivers in the world the (Contraloría 2003b).

Blackman et al. (2006) and Blackman (2009) in an attempt to analyze the problem identified four main dimensions to the domestic waste water situation prevalent in the country: (i) inadequate wastewater collection as many households are not connected to municipal sewer systems. This implies that a quarter of Colombia's urban population which comprises three-quarters of its total population e does not have access to sewer systems; (ii) lack of wastewater treatment in many municipalities such that collected wastewaters are generally not treated (see **Table 5**). As of 1999, only 16% of Colombia's 1089 municipalities had operating treatment plants with less than 1% of municipal wastewater generated nationwide subjected to any form of treatment (Contraloria, 2003a). As such inefficient operating condition of many of the existing wastewater treatment plants is common. In a study by the Ministry of Development out of the 40 municipal wastewater treatment plants sampled only 40% were functioning in compliance with emissions standards; and (iv) the reliance of most of the wastewater treatment exclusively on high-cost, high-technology, conventional treatment plants. There are few low-technology, low cost solutions, such as lagoons, anaerobic processes, anaerobic filters, and seasonal stabilization reservoirs for agricultural reuse (Libhaber and Foster 2002). On the other hand, studies have revealed that most of the industrial wastewaters generated with the country are not treated (IDEAM, 2002b; Carrasquilla and Morillo, 1992).

Table 5: Wastewater Treatment as a Percentage of Total Flow in Colombia - 1999
(Adapted from Rodriguez et al., 2008)

Parameters	**Estimates**
Urban Population	29,386,109
Water consumption (m^3/day)	6,788,191
Wastewater flow (m^3/day)	5,407,044
Treated wastewater flow (m^3/day)	11,680
Percentage of wastewater treated	0.21

Therefore, managing the impact of these factors on a river basin and finding optimum mitigating measures, are challenges for modern urban planning and engineering within urban center in the country. With expected per capita water consumption for 2010 put at 88 liters per day down from approximately 150 liters per day in 1990 and 1995 and 94 liters per day in 2004 (EAAD, 2006), the water consumption rate in the Bogota City as of 2008 was put at 14 m^3s^{-1}, where 20% was for commercial activities. The return factor (ratio between wastewater flow and water consumption) was put at approximately 0.85 (Rodriguez et al., 2008). As recommended by Marchettini et al., 2007, sound waste management policy based on the principles of sustainable development where waste is viewed as a potential resource to be reused such that the integrated waste management plan makes full use of all available technologies sustainably needs to be implemented. Waste here is broadly defined to include all unwanted material left over from manufacturing processes or refuse from places of human or animal habitation. Municipal wastewater, whose properties make them dangerous or potentially harmful to human health and the environment, conveniently fits within this category.

2.7.2 WASTEWATER MANAGEMENT POLICY DESIGN

Environmental management system in Colombia is decentralized based on the command-and-control regime. The ultimate legal authority is the Constitution: all other legal instruments must comport with its general principles and specific details. Laws are next in the hierarchy. The MMA is the principal environmental regulatory authority at the national level with responsibilities ranging from formulating, managing, to coordinating water-quality policies and programs. 33 Regional Autonomous Corporations (*Corporaciones Autónomas Regionales - CARs*) and five Urban Environmental Authorities (*Autoridades Ambientales Urbanas – AAUs*) are the principal regional environmental authorities in Colombia's most populous cities endowed with considerable fiscal and policy autonomy meant to insulate for implementing and enforcing the MMA programs and policies (Blackman 2009). Among the constitutional provisions most relevant to waste management are those that assign the Colombian state the following responsibilities:

- To protect environmental diversity and integrity;
- To preserve special ecologically important areas, including national parks;
- To plan the management and exploitation of natural resources to guarantee sustainable development, conservation, restoration, or substitution;
- To prevent and control environmental deterioration; and
- To impose legal sanctions and require reparation when damage is caused.

Annex 17 shows the legal frameworks and regulations on water quality regulation in Colombia and urban centers. On the whole, Colombians waste management policy is based on registration and permits, discharge standards, licensing, discharge fees, and quality standards. The design of the permitting and discharge standards is quite conventional: the environmental authority identifies polluters and issues permits; polluters must abide by a set of discharge standards; environmental authorities monitor compliance with the standards through a mixed system of self-reports and random verifications; and environmental authorities impose sanctions for noncompliance, including closures and fines (Blackman et al, 2006). The current legislation on discharge of wastewater in water bodies is presented in **Table 6.**

However, due to environmental authorities poor inventories of dischargers, a consequence of the fact that many polluters in Colombia are small and informal (unlicensed and unregistered such as on-farm coffee-processing and automotive repair shops), compilation of emissions inventories are particularly challenging. Monitoring and enforcement of discharge standards are equally inefficient and ineffective given that out of the 30 pollutants covered by Decree 1594 of 1984, CARs and AAUs only monitor discharges of two (2): BOD and TSS. COD and other substances such as coliforms are not monitored, much less regulated. On the other hand, although EIA is a requirement for most projects subsequent monitoring for compliance is lacking (Blackman 2009).

Table 6: Decree 1594 of 1984: Standards for Wastewater Discharges – Discharges into a water body

Pollutant/characteristic/CMP	Existing User	New User
pH	5 to 9 units	5 to 9 units
Temperature	< 40°C	< 40°C
Floating materials		Absent
Fats and oil	Removal > 80 % in load	Removal > 80 % in load
Domestic or industrial suspended Solids	Removal > 50 % in load	Removal > 80 % in load
Biochemical demand of oxygen:		
For domestic residues	Removal > 30 % in load	Removal > 80 % in load
For industrial residues	Removal > 20 % in load	Removal > 80 % in load
Maximum permissible load (CMP)	According to what is established in articles 74 and 75 of the present Decree	

This study contributes retrospectively a risk assessment (demonstrates the connection between wastewater and ecosystem quality), benefit-cost analysis (quantify the benefits of avoiding the effects indicated by the risk assessment as well as the costs of complying with the policy) and cost-effectiveness analysis of the urban wastewater management policy by evaluating one of the plants used to achieve this policy goal. This tests the adaptability of the management approach to environmental and natural resources policy.

3 MATERIALS AND METHOD

3.1 DESCRIPTION OF STUDY AREA

Bogota city, the largest city in Colombia, is located on the west of the Savannah of Bogotá (*Sabana de Bogotá*), 2640 meters above sea level. The average temperature is 14.0 °C (57 °F), varying from 3 to 25 °C (37 to 77 °F). Dry and rainy seasons alternate throughout the year. The driest months are December, January, February and March. The warmest month, January, brings the maximum temperatures up to 25 °C (77 °F). The region has an annual rainfall of 946 mm. Bogotá, is the capital city of Colombia, as well as the most populous city in the country, with an estimated 7,304,384 inhabitants as of 2009.

Domestic wastewater management in the Bogota city is based on the conventional approach of collecting the wastewater in traditional drainage systems and transferring it to a treatment plant. However, a variety of decentralized methods exist, which are being used in both rural and suburban areas. Decentralized and also ecological methods generally provide simple, low-cost and low maintenance methods of treating domestic wastewater in small towns within the country as a whole.

3.2 CASE STUDY - THE SALITRE WASTEWATER TREATMENT PLANT (WWTP)

The El Salitre Wastewater Treatment Plant (WWTP) is located near the Juan Amariilo River and was designed to treat domestic wastewater generated from the north of the Capital District drains an area of about 13964 ha **(see Figure 5).** The Salitre River contributes 30% of the 90% (from Fucha and Tunjelo sub-catchements) pollution load that reaches the Bogota River with the Torca, Conejera, Jaboque, Tintal y Soacha sub-catchment areas contributing the remaining 10% (DAMA, 1995). The plant is the first component of the sanitation scheme for the Bogota River in accordance with the resolution 817 of 1996 of the

MAVDT. The facility treats domestic wastewater from approximately 2.2 million inhabitants corresponding to about 30% of the total population of the city discharged from homes, offices, schools, universities etc.

This wastewater is captured by a sewer system that partially separates residual wastewater from rainwater**.** It has been described to have an efficiency of 60% total suspended solid (TSS) and 40% biological oxygen demand (BOD_5) removal with the generation of 13500 m³/d of biogas and 165 ton/d of biosolid respectively. The plant applies primary and chemically advanced method coupled with three anaerobic digesters to treat the resultant bio-solids from the wastewater (**see Figure 6, and Tables 7a, 7b and 7c**). This plant is selected for this case study because of its purported vital role in the purification of the highly contaminated Bogota River.

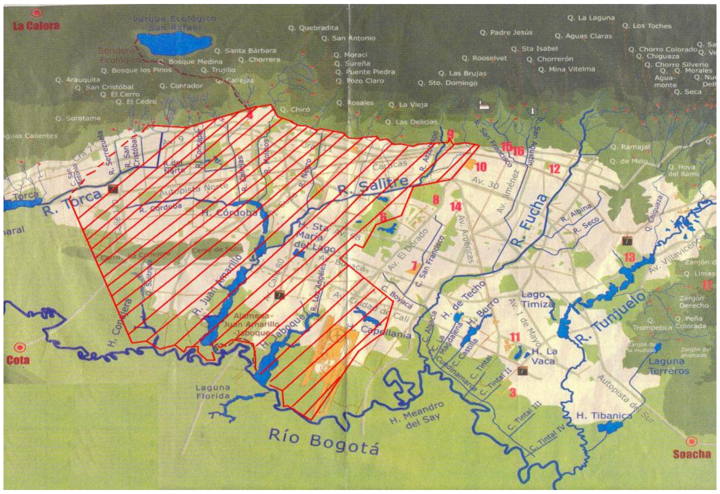


Figure 5: Map of the Bogota river watershed showing the area served by the El Salitre WWTP – Area in red lines (Source: EAAB Report No. 5, 2010)

3.2.1 TREATMENT DESCRIPTION

As previously mentioned, the El Salitre WWTP uses physical/chemical treatment. Wastewater is collected and channeled to the plant in a separated sewer system. Storm water is conducted through an open channel system to wetlands and rivers.

3.2.1.1 WASTEWATER INTAKE AND PUMPING

Wastewater initially enters a chamber equipped with a moat for the removal of heavy and coarse solids. Then, the wastewater is screened for other large solids by means of bars. Archimedes Screw of 3.10m in diameter pumps the screened wastewater to an elevation of nearly 10m. Two composite samples are taken daily for the characterization of the wastewater at this point. The general treatment system as presented in Figure 6 is divided into 3 lines:

3.2.1.2 PRETREATMENT

- **Water Line:** The treatment for the water line consists basically of pretreatments processes. This involves: (a) fine blooming by four automatic grids; (b) sand removal which allows the removal of sand and other inert materials (glass, seeds) and degreasing. In addition, clarification of the wastewater via coagulation – flocculation is carried out through the use of ferric chloride and dry polyacrylamide anionic polymer at an average dose of 32 mg / L and 0.50 mg/L respectively; (c) channeling of the wastewater to the primary sedimentation tanks or clarifiers; (d) Each of the eight (8) clarifiers is equipped with a sweep bridge to scrape the mud sludge that collects at the bottom and concentrate it in a hopper or front pocket. This sludge is transported through the pumping stations to the primary sludge thickener for subsequent treatment; (e) a pump that send the sludge to the gravity thickening stage automatically removes the mud sludge from two primary clarifiers; (f) the clarified water is collected for subsequent discharge into the Bogota River, thus ending the treatment in line for water.

Emergency diversion channel: This is an excess system **(see Annex 18)** which is opened when the WWTP receives excess wastewater beyond its capacity. The diverted wastewater undergoes pretreatment before being discharged into the Bogota River.

- **Sludge Line:** The processes involved are: (a) thickening of the mud sludge to increase its concentration before digestion. The retrieved wastewater is returned to the start of the treatment process. Two thickeners are used and each has a diameter of 29m and a height of 4m; (b) the extraction of the thickened sludge, with a TS concentration of about 40 g/L, to a collection pit, where they are pumped at a rate of 1300 m^3/day to three digesters. The three digesters have a capacity of 8500 m^3 and biological stabilize the sludge for approximately 22 days, at a temperature of 35 ºC. A homogeneous sludge mixture is achieved by gas agitation. Biogas is re-circulated and injected into the center of each digester, ensuring an intimate contact between the digested sludge and sludge oil. The temperature inside the digester is maintained above 35 º C using energy from biogas combustion where the sludge is heated in tubular water-sludge countercurrent heat exchangers; (c) the storage of the digested sludge in a tank equipped with submersible mixers for subsequent extraction to the dehydration process; (d) solid-liquid separation of sludge is carried out to obtain a sludge cake with a solids concentration of approximately 30% aimed at volume reduction volume and easy transportation and disposal. Cationic polymer is used in this operation. Wastewater recovered from the sludge thickening and dehydration is re-circulated into the processing head once gathered at this pumping station. Two diesel powered internal combustion engine generator sets which starts in power failure serves as an emergency system.

- **Biogas Line:** Daily the biogas generated is recycled for the agitation of the digester and to power boilers that are part of the heating system. Biogas produced during the treatment process is stored in a 1030m^3 gas meter while excess gas is flared.

Table 7a: General demographic and geological characteristics of the study area (DAMA, 1995).

Described Characteristics	Value			
Basin Area, ha	Basin	Total	Urban	
	Salitre	13964	9026	65%
	Torca	6592	964	15%
	Conejera	2646	173	7%
Population size served	Design Value	Actual Value	2020 (Projected)	
	1300000	2200000	2450000	
Total population of the city served by the WWTP, %	30			
Population density, inh/ha	158			
Population growth rate, %	2.2			
Maximum daily Precipitation, mm/d	267			
Average Annual Precipitation#, mm	802			
Temperature, °C	Average	Maximum	Minimum	
	13.5	29	7,1	
Average Relative Humidity	82%			
Average wastewater flow rate, m3/s	1991	2000	2010	2020
	3.97	5.01	5.79	6.43

The months of January/February and June/August are the driest while the wet periods are during the months of April/May and October/November.

Table 7b: General design and actual parameters of the El Salitre WWTP.

Parameters	Actual value*	Design value#
Plant área, km^2	0.1	0.1
Population equivalent, p-e	2200000	2450000
Average daily raw wastewater flow, m^3/d	353126	345600
Flow rate, m^3/s	4,0	4
Average dry weather flow (ADWF), $m^3\ S^{-1}$	2,7	2,5
Peak wet weather flow (PWWF), m3 s^{-1}	9,4	10
Average Hydraulic Retention Time, days$^{\Delta}$	27	22
Influent TSS, mg/l	219	356
Influent BOD_5, mg/l	257	274
Effluent TSS, mg/l	87	214
Effluent BOD_5, mg/l	152	110 - 123

* Average values from the Plant operations. # EAAB, 2007; DAMA, 1995. Δ Value for individual reactor.

Table 8: General plant operational parameters of the El Salitre WWTP.

Parameters	Value
Average daily raw wastewater flow, m^3/d	353126
Average dry weather flow (ADWF) - m^3 d^{-1}	233280
Peak wet weather flow (PWWF) ratio - m^3 d^{-1}	584288
Average Plant treatment flow capacity, m^3/s	4.0
Type of treatment process	Primary and chemically advanced treatment
Capacity of each of the 3 biological digesters, m^3	8500

For a better understanding and evaluation of the impacts of the WWTP operations, the plant processes were further divided into three main parts **(see Figure 6)** and the inventory fluxes taken into account in the water, sludge and biogas lines are shown in **Table 9.**

- The water line
- The sludge line and
- The biogas line.

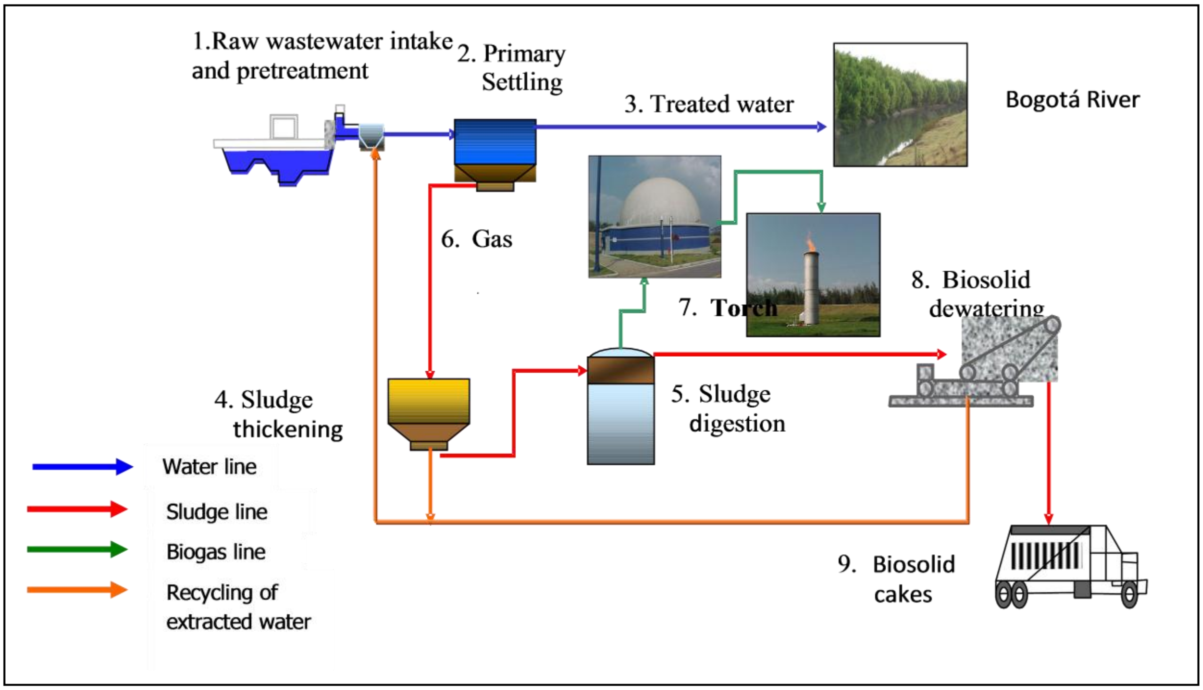


Figure 6: Scheme of the wastewater treatment processes at El Salitre WWTP showing three of the four lines used for the study (adapted from EAAB, 2010).

3.3 METHODOLOGY

The Life Cycle Assessment (LCA) methodology based on Sustainable Development Indicators (SDI) to provide a holistic assessment was chosen for evaluating the entire life cycle of the sustainability of the El Salitre municipal wastewater treatment technology. This method has been shown to provide stringent assessment of environmental sustainability by allowing for refinement/replacement of indicators through Case Studies evaluation.

4.3.1 SCOPE AND GOAL DEFINITION

The starting point was to specify the overall purpose (goal and scope) which in this study is the assessment of the environmental sustainability of the urban wastewater treatment system of the El Salitre Plant in order to support and improve decision-making at the level of watershed management and by implication the development a more sustainable wastewater management practices. This study was limited to the assessment of the sustainability of the WWTP along the life cycle of the operational phase of the WWTP.

Table 9: The inventory fluxes taken into account in the water, sludge and biogas lines of the El Salitre WWTP

Water line	Sludge line	Biogas line
Average daily volume of raw wastewater treated (m^3)	Average daily primary load generated (m^3/month)	Average daily air-borne emissions at the boilers - SO_2, H_2S, PM, CO, and NO_x (m^3/day)
Average daily volume of treated wastewater (m^3)	Average daily load treated at the anaerobic digesters (kg/day)	Average annual air-borne emissions at the electric generators - SO_2, H_2S, PM, CO, and NO_x (m^3/day)
% Biochemical oxygen demand (BOD_5) Removal	Average daily generated Biosolid (sent to Predio El Corzo) (kg/day)	Average daily air-borne emissions at the torch – SO_2, H_2S, PM, CO, and NO_x (m^3/day)
% Total Suspended solid (TSS) removal	Average daily generated solids (sent landfill) (kg/day)	% Average daily methane (CH_4) in biogas generated
% Nitrogen removal	Biosolid average physicochemical concentration	% Average annual carbon dioxide (CO_2) in biogas generated
% Total phosphorus (TP) removal	Biosolid average microbial Concentration	% Average annual nitrous oxide (N_2O) in biogas generated
% pathogens removal	Analysis of the tendencies at the biosolid application – Soil	Emissions from biogas flaring – CO, NO_x, SO_2
Nuisance produced by smell	Analysis of the tendencies at the biosolid application – Plant	% of biogas used for heat generation

3.3.2 SYSTEM BOUNDARIES AND THE FUNCTIONAL UNIT DEFINITION

The functional unit is defined to quantify the environmental impacts associated with the various management regimes and thus provide a basis for comparing the results. The life cycle system boundary selected for this study, in accordance with the definition of Foley et al., (2010), included the first-order processes (direct atmospheric emissions, effluent discharges) and some second order processes (purchased energy generation and chemical use) **(see Figure 7).** The geographical boundary for the wastewater treatment system started from the entrance of the raw wastewater and ends with discharge of treated storm and wastewater to the aquatic ecosystem, disposal of sewage sludge, either to landfill or agricultural land **(see Figure 5).**

A time perspective of six (6) years was considered to cover only the operational phase of the wastewater system using the most recent data available, from the years 2004 to 2010. The main functional unit that was used in the research is the treatment of one cubic meter of wastewater treated. Temporal, spatial and life cycle boundaries evaluated aimed at the provision of data for the comparison of the plant with other of integral solutions.

3.3.3 SELECTION OF SUSTAINABILITY DEVELOPMENT INDICATORS (SDIs)

A framework to guide the choice and identification of sustainability development indicators (SDIs) for the selected WWTP was developed. The well-established and standardized life cycle assessment (LCA) framework was used to evaluate the impacts or benefits of the WWTP on the environment in relation with the selected functional unit. Following the development of the framework, selection of appropriate SDI was carried out for the LCA Case Study through literature review and study of the characteristic of the selected WWTP and the El Salitre watershed. The United Nations Department of Policy Coordination and Sustainable Development’s criteria cited by Muga and Mihelcic (2008) were used to select the most appropriate indicators.

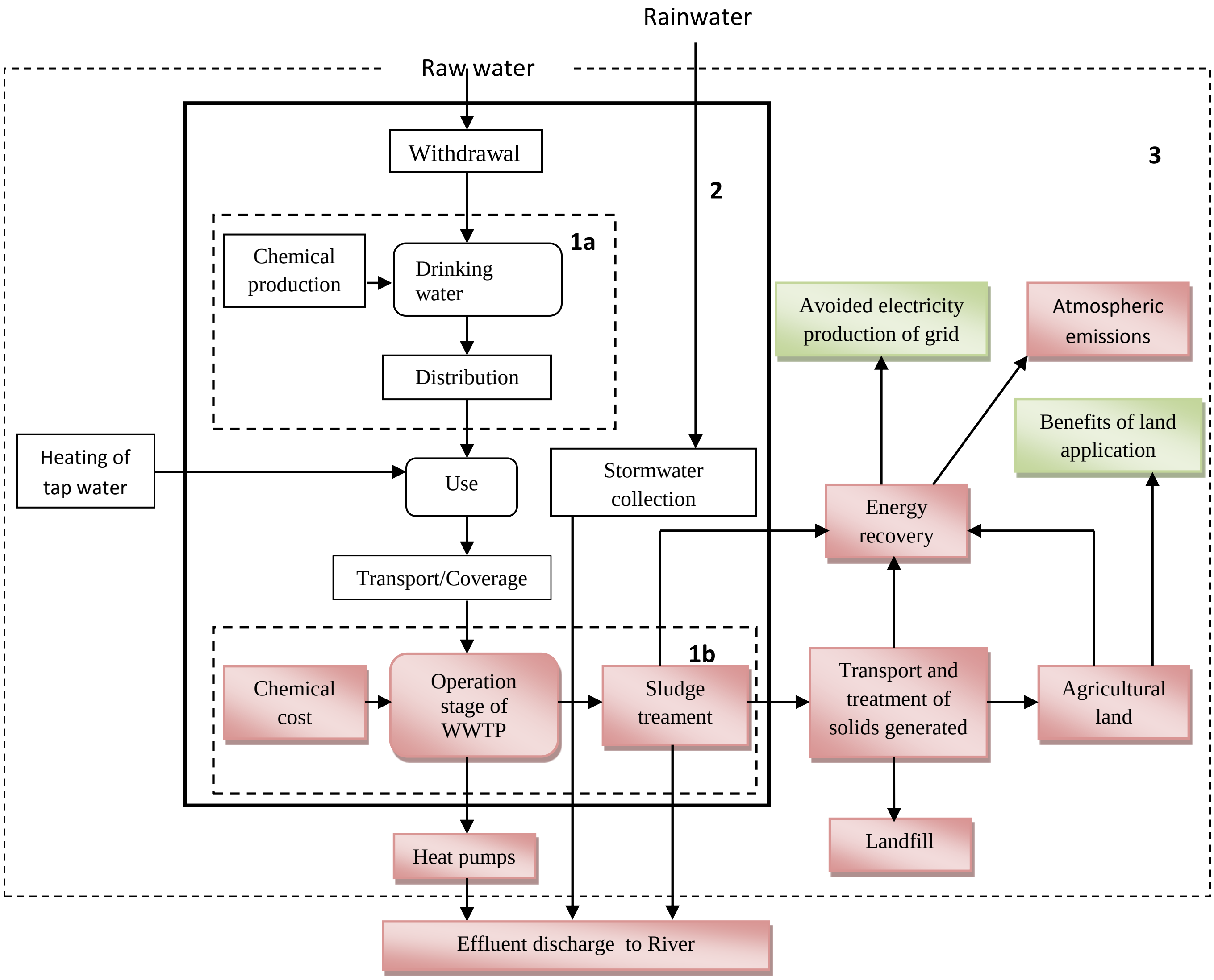


Figure 7: Overview of system boundaries for the urban water system used in the development of environmental sustainability indicators through LCA. The arrows indicate flows of energy and materials through the system. *(1a) Drinking water treatment. (1b) Wastewater treatment. (2) Anthropogenic treatment, use and handling of urban water. (3) The urban water system and surrounding systems. The colored blocks show the boundaries used for this study (Adapted from Lundin and Morrison*
🟥 First-order Processes 🟩Second-order processes

3.3.4 ADOPTED SDIs

A limited but comprehensive set indicators based on four SDI categories was selected to address the most important aspects of the WWTP: functional, environmental, economic and socio-cultural indicators respectively. While the economic, environmental, and social–cultural indicators were used to give insight into the efficiency of the solution, the functional indicators were applied to determine the effectiveness of the solution.

3.3.4.1 *The functional indicators:* These are applied were applied to evaluate the performance of the WWTP with respect to the plants minimal technical requirements.

1. *Effectiveness: These indicators* were used to evaluate the minimal technical requirements and influent-effluent quality.
    1.1 Load of pollutants entering the WWTP per inhabitant connected ($gd^{-1}inh^{-1}$), per catchment area ($gd^{-1}m^{-1}$), per population density ($gd^{-1}inh^{-1}m^{2}$).
    1.2 Percent of energy consumption per volume of treated wastewater ($kWhm^{-3}$).
    1.3 Quantity of treated wastewater as a percentage of total quantity of wastewater (%)
    1.4 Total chemical use per day per volume of treated wastewater ($gd^{-1}m^{-3}$): this evaluates the environmental burden created by the consumption of synthetic chemicals given that chemicals require additional resources and energy for manufacture and transportation to the WWTP.
2. Efficiency Indicators were applied to evaluate the plant's pollutants removal capacity.
    2.1 WWTP removal efficiencies of pollutants (%)
    2.2 Energy recovered from the WWTP ($kWh\ inh^{-1}d^{-1}$).
    2.3 Actual PE as a percentage of design PE
    2.4 Ratio of pollutants in wastewater.
3. *Adaptability/Flexibility Indicators* were used to analyze the ability of the plant to cope with fluctuations in the influent, climate and ecosystem influence on system performance and possibility to extend the system in capacity or with additional treatment.
    3.1 Hours that the emergency diversion channel was opened per day – hrs/d.

    3.2 Number of times that the emergency diversion channel was opened per day – No./d.

4. *Maintenance Indicator* which assesses plant required maintenance (Number of system breakdown for maintenance per day (No.d^{-1})
5. *Reliability* (sensitivity of the system to malfunctioning of equipment and instrumentation).

3.3.4.2 *The environmental indicators:* They were employed to measure the plant's environmental performance with respect to the technical systems.

1. Effluent quality: this is applied to measure the quality and by extension the impact of the WWTP effluent on the receiving waters.
    1.1 Ratio of total pollutants in the receiving water compared to the WWTP effluent: This offers a measure of the plant to achieve its objective and the self-purification capacity of the receiving water bodies. Low values indicate high capacity, high values indicate low capacity.
2. Sludge quality: This evaluates the management process of the sludge line through the analysis of the biosolid quality produced.
    2.1 Ratio of solids sent to landfill compared to land application: Applied to indicate the amount of nutrients lost over time through the landfilling of solids compared with P and N reutilization through the reuse of biosolids in land application.
    2.2 Phosphorus (P) and nitrogen (N) recycling through the reuse of biosolids: measures the quantity and percentage of nutrients in terms of P and N recycled through land application, compared with total biosolids production over time by evaluating the quantity (kilogram) of N and P recycled per kilogram of biosolids (dry weight) through land application as compared with total biosolids production per day.
    2.3 Discharge of selected heavy metals to soils: Measure of the heavy metal toxicity compliance through the comparison of the heavy metal content of the soils subjected to biosolids application as compared to the biosolid heavy metal content.

3. Global warming (GW): This was used to define the contribution of greenhouse gases to global warming over the time period from the gaseous emissions from operations and transport of the generated solids.
    3.1 Gas reutilization
    3.2 Gas emission in kg CO_2 equivalent per day.
4. Public health risk (PHR): this is used to indicate the protection of public health through the use of the sanitary installation, collection, transport, treatment and destination of the treated products. This criterion evaluates the public health risk of the available technology to prevent inhabitants contact from faeces, urine, raw wastewater, treated wastewater or sludge.

3.3.4.3 *The economic indicators:* They were used evaluate the costs effectiveness of operational and maintenance phase of the WWTP. The cost categories used in this study to evaluate the cost effectiveness are:

1. Total costs per volume of wastewater treated ($\$m^{-3}d^{-1}$)
2. Operational and Maintenance costs per volume of wastewater treated ($\$m^{-3}d^{-1}$)
3. Energy costs per volume of wastewater treated ($\$m^{-3}d^{-1}$)
4. Chemical (polymer) costs ($\$m^{-3}d^{-1}$)
5. User cost ($\$m^{-3}$)

3.3.4.4 The socio-cultural indicators are

1. *Community Size Served:* This was applied to evaluate the aptness of the treatment system selected, its capacity and therefore its sustainability given that an increased population often means a larger plant capacity.
2. *WWTP Footprint Compared to Wastewater Treated:* This represents the efficiency of surface occupation of WWTPs, specific for the volume of treated wastewater. This is critical factor in densely populated cities and in open lands, where larger processes use agricultural space and ultimately destroy natural habitat.

3. *Labor Required to Operate the WWTP:* this evaluated the staff required to operate and maintain the WWTP based on plant capacity.
4. Aesthetics - Measured Level of Nuisance from Odor:
5. *Community participation:* This was applied to assess the stimulation of sustainable behavior by increasing the end-user's awareness and concern for the city sanitation plan. The criterion used were:
   - 5.1 Ratio of total population served to total visits to the WWTP and
   - 5.2 Ratio of employment generated in the WWTP community (ratio of total staff)
6. *Expertise (level of education):* Given that increased education is generally valued as an important indicator for sustainability especially with regards to the level of mechanization of most treatment system, this was used to assess the WWTP's operator level of education. The parameters used were
   - 6.1 Professionals - Ratio of Total staff
   - 6.2 Technical - Ratio of Total staff
   - 6.3 Others - Ratio of Total staff

4 LIFE CYCLE INVENTORY RESULTS

The data for the evaluation of the sustainability of the WWTP was collected from the database of the Bogota Water and Sewage Company (*Empresa de Acueducto y Alantarillado de Bogotá* – EAAB; the operators of the wastewater treatment plants), existing data in published LCA studies, government publications, open literature and public databases based on the indicator categories. In addition, field visits were made to the water treatment plants (WWTP) for data collection and validation and interviews with the plant operators. The secondary data was collected in accordance with the five identified environmental and technical system boundary of the life cycle of urban wastewater management processes as suggested by Lundin and Morrison, 2002 (**see Figure 7**):

- Collection and characteristics of wastewater
- Treatment process of the collected wastewater
- Purchased electricity generation/chemicals
- Handling of by-products such as solids, biosolid, biogas and effluents and
- The services which included maintenance (diesel fuel, lubricating oil, and lubricating tallow), packaging (biosolids disposed of in landfill) and transportation.

Daily loadings into the WWTP were calculated from measured flow rates and concentration data from the plant's operations database. The table below shows the inventory data corresponding to the water, sludge and biogas lines of the El Salitre WWTP. Furthermore, presented in Table 11 are the selected inventory data for the WWTP from the year 2004 through to 2010. Despite the fact that these inventory data could be employed for the life cycle impact assessment (LCIA), analysis was carried out using available end-point LCIA methodology to evaluate the sustainability of the WWTP configuration and treatment processes. Some of the data used were calculated based on formulas from literature.

4.1 ESTIMATING RECOVERY EFFICIENCY OF POLLUTANTS

The phosphate recovery efficiency for the WWTP was calculated using the equation below:

$$P\ recovery\ (\%) = \frac{([PO_{4.} - P]i(Q_i) - [PO_4 - P_e]e(Q_e))}{([PO_{4.} - P]i(Q_i)} \times 100\%$$

Where $[PO_{4.} - P]i$ the concentration of PO$_4$-P in the influent raw sewage is $[PO_4 - P_e]e$ is the concentration of PO$_4$-P in the effluent water, Q$_i$ and Q$_e$ are the influent and effluent volumetric flow rate respectively (Mavinic et al., 2007). A similar calculation was employed for the calculation of nitrogen recovery efficiency of the WWTP.

4.2 ESTIMATING CH_4, CO_2 AND N_2O EMISSIONS FROM WASTEWATER AND SLUDGE TREATMENT UNITS

Carbon dioxide (CO_2) Methane (CH_4) and nitrous oxide (N_2O) emissions that are released from wastewater and sludge treatment Units (during the treatment processes and discharging of waste water at the WWTP, from the water and sludge lines respectively), were calculated using the U.S. Environmental Protection Agency (EPA) GHG Emissions Estimation Methodology for Selected Biogenic Source Categories as presented in the equations below. This approach estimates the sludge digester's CO_2 and CH_4 emissions assuming all organic carbon removed from the wastewater is converted to CO_2, CH_4, or new biomass based on the feed to the wastewater treatment process given that the only solids entering the unit are those generated in the wastewater treatment system.

$$CO_2 = 10^{-3} \times Q_{WW} \times BOD_5 \times Eff_{BOD_5} \times CF_{CO_2} \times \left[\lambda\,(1 - MCF_s \times BG_{CH_4})\right]$$

$$CH_4 = 10^{-3} \times Q_{WW} \times BOD_5 \times Eff_{BOD_5} \times CF_{CH_4} \times \left[\lambda\,(1 - MCF_s \times BG_{CH_4})\right]$$

$$N_2O_{WWTP} = Q_{WW} \times TKN_i \times EF_{N_2O} \times {}^{44}\!/_{28} \times 10^{-3}$$

where:

CO_2 = Emissions of CO_2 (kg CO_2/day)

CH_4 = Emissions of CH_4 (kg CH_4/day)

N_2O_{WWTP} = N_2O emissions generated from WWTP process (kg N_2O/day)

10^{-3} = Units conversion factor (Mg/g)

Q_{WW} = Wastewater influent flow rate (m^3/day)

BOD_5 = Oxygen demand of influent wastewater to the biological treatment unit determined as BOD_5 (mg/L = g/m^3)

TKN_i = Amount of TKN in the influent (mg/L = g/m^3)

Eff_{BOD5} = Biological oxygen demand removal efficiency of the biological treatment unit

CF_{CO2} = Conversion factor for maximum CO2 generation per unit of oxygen demand = 44/32 = 1.375 g CO_2/ g oxygen demand

44/28 = Molecular weight conversion, g N_2O per g N emitted as N_2O

CF_{CH4} = Conversion factor for maximum CH_4 generation per unit of oxygen demand = 16/32 = 0.5 g CH_4/ g oxygen demand

EF_{N2O} = N_2O emission factor (g N emitted as N_2O per g TKN in influent) = 0.0050 g N emitted as N_2O/g TKN

MCF_S = methane correction factor for sludge digester, indicating the fraction of the influent oxygen demand that is converted anaerobically in the digester = 0.8 (IPCC, 2006).

BG_{CH4} = Fraction of carbon as CH_4 in generated biogas (default is 0.65).

λ = Biomass yield (g C to biomass/g C consumed in the wastewater treatment process) = 0.1

Emissions of the greenhouse gases (GHGs), methane (CH_4), and nitrous oxide (N_2O) were calculated, and expressed as CO_2-equivalent emissions (CO_2-eq).

The contributions of CH_4 and N_2O to the greenhouse effect were converted to CO_2 –equivalent using the Global Warming Potentials as established by the International Panel on Climate Change in the Fourth Assessment Report and presented in **Table 10** (Forster P. et al, 2007) by

$$CO_{2eq} = \sum_{i=1}^{n} (GHG_i \times GWP_i)$$

where

CO_{2e} = Emissions in carbon dioxide equivalents (kg/day)

GHG_i = Emissions of GHG pollutant "*i*" (kg/day)

GWP_i = GWP of GHG pollutant "*i*"

n = Number of GHG emitted from the source.

Table 10: Global Warming Potentials for the selected identified greenhouse gases.

Greenhouse Gas (GHG)	Chemical Formula	Global Warming Potential (GWP)
Carbon dioxide	CO_2	1 kg CO_2 = 1 kg CO_2-eq.
Methane	CH_4	1 kg CH_4 = 21 kg CO_2-eq.
Nitrous oxide	N_2O	1 kg N_2O = 310 kg CO_2-eq.

4.3 ESTIMATING CH_4 AND CO_2 EMISSIONS FROM COMBUSTION OF BIOGAS AT THE TORCH

For the estimation of CO_2 emission from the torch used for flaring the biogas produced from the digesters, the equation below was used with a destruction efficiency of 95%. This value is based on the assumption that a small portion of the recovered CH_4 was not converted to CO_2, either due to incomplete combustion of the CH_4 (i.e., the destruction efficiency of the torch) or due to bypassing or otherwise not operating the torch.

$$X = R_{CO_2} + \left(R_{CH_4} \times DE \times \frac{44}{16}\right) + \left(R_{N_2O} \times DE \times \frac{44}{28}\right)$$

where:

X = CO_2 emissions from recovery (kg CO_2/day)

R_{CH4} = Quantity of CH_4 recovered (kg CH_4/day)

R_{CO2} = Quantity of CO_2 recovered (kg CO_2/day)

DE = Destruction efficiency (95%)

44 = Molecular weight of CO_2 (kg/kg-mol)

16 = Molecular weight of CH_4 (kg/kg-mol).

28 = Molecular weight of N_2 (kg/kg-mol).

The total GHG emissions from the WWTP are the sum of the CO_2 emissions from the flare and the CO_2 emissions from the WWTP unit processes.

Literature data from Muga et al., (2008) was used to provide for alternative analysis configuration and improvement evaluation.

4.4 NORMALIZATION OF INVENTORY DATA

The data from inventory analysis was normalized to increase the cohesion of different indicators as such reducing and eliminating data redundancy. Normalization is an optional step in the weighting between impact categories. The procedure provides the decision maker with a measure of the relative contribution from a product system to the impact categories. The normalization approach suggested by Agudelo et al., (2007) was used to bring the inventory data to a common scale of 1 to 100 indicating increasing or unsustainable impact by applying data average, maximum and minimum values for the parameters evaluated in accordance with the equation below:

$$d_{score} = \left| 1 - \frac{(d - d_{min})}{(d_{max} - d_{min})} \right| \times 100$$

Where

d_{score} = normalized value

d = Average value from data analysis.

d_{max} = maximum value of analyzed inventory data.

d_{min} = minimum value of analyzed inventory data.

I I = absolute value

4.5 SUMMARY OF INVENTORY DATA FROM THE WWTP

Table 11: Summary of average data for the water, sludge and biogas lines of El Salitre WWTP.

Item	Value
Influent water-borne pollutants	
TSS	221 mg/L
BOD$_5$	259 mg/L
COD	530 mg/L
Nitrates (NO_3^-)*	0.67 mg/L
Nitrites (NO_2^-)*	0.016 mg(L
TKN*	54 mg/L
P, total*	8.8 mg/L
Fecal Coliform$^{\Delta}$	1.94 x 10^7 UFC/100mL
Chemical used (Anionic polymer)	0.51 g/m^3
Load characteristics from Primary Settling Tank	5355 m^3
Load volume	17446.08 mg/L
TS	6.9
pH	27.77 g/m^3
Chemical used ($FeCl_3$)	
Load characteristics from Sludge Thickening	1304 m^3
Load volume	83.71 g/L
TSS	47.24 g/L
VS	6.5
pH	
Digester Load	
Volume of load to digesters	1092 m^3
TS	81.25 g/L
VS	35.89 g/L
pH	7.4
Alkalinity	2594.52 mg $CaCO_3$/L
Effluent water-borne pollutants	
TSS	87 mg/L
BOD$_5$	152 mg/L
COD	295 mg/L
Nitrates (NO_3^-)*	0.74 mg/L
Nitrites (NO_2^-)*	0.02 mg/L
TKN*	50 mg/L
P, total*	5.44 mg/L
Fecal Coliform$^{\Delta}$	1.15 x 10^7 CFU/100mL
Energy use	kW/h
Average annual consumption$^+$	8404831.65
Average monthly consumption$^\#$	699593.28
Average monthly cost (June 2004-Sept. 2010)	138509725.5

Total Gas Emissions	12552.37 m^3/day
Solid Emissions	
Biosolid	420.0 kg/m^3
Fine Residue	2.50 g/m^3
Thick Residue	2.90 g/m^3
Sand	1.48 g/m^3
Fat	5.49 g/m^3
Biosolid Generated	
Volume flow rate of biosolid	2506.35 tons/yr
Humidity	71.61 %
Dryness	32.46 %
TS	259640.0 mg/kg
VS	128175.35 mg/kg
Biosolid Density	0,89 g/m^3
Chemical used (Anionic polymer)	4,14 Kg/ton MS

Data presented on this table is based on data from June 2004 – September 2010 and calculated on daily bases.
* Data was calculated from January 2007 – August, 2010. [+] Data was calculated from January 2005 – December, 2009.
[#] Date was calculated from June 2004 – September 2010. [Δ] Date was calculated from January 2007 – August 2010.

4.6 LIFE CYCLE IMPACT ASSESSMENT (LICA)

After data inventory, the information gathered was evaluated against desirable characteristics such as their relevance to the sustainability of the selected urban water system, their ability to predict potential problems and the availability and quality of information using three (3) approaches:

- Assessment based on the criteria issues for the Life Cycle Impact Assessment (LCIA) on the SDIs **(see Table 12**).
- Normalization of inventory data for the SDIs.
- Target plots showing the four selected dimensions of wastewater sustainability.

4.7 FUNCTIONAL SUSTAINABILITY

4.7.1 QUANTITY OF TREATED WASTEWATER AS A PERCENTAGE OF TOTAL QUANTITY OF WASTEWATER

This was used to compare the total volume of wastewater treated daily in the WWTP with the total volume of wastewater generated within the catchment area. Based on average water consumption of the Bogota city, now put at about 200L/Inb/day (IDEAM, 2010), the average sewage flow rate was projected to be 5.79 m3/s for the El Salitre water catchment area (DAMA, 1995). The calculation was based on a basic sanitary flow of 0.85 and 0.1 return factors (the ratio between wastewater flow and water consumption) for domestic and industrial/commercial water use respectively with an infiltration flow rate and runoff due to wrong connections of 0.1L/s/ha. Based on this value, a daily 497664 m^3 of wastewater generated within the catchment area it can be observed in **Table 12** that on the average, the WWTP treats about 41% of the total wastewater generated from the catchment area on a typical day. This implies that more than half of the wastewater generated within the catchment area (60%) still goes on untreated as such discharged into the El Salitre River.

Table 12: Comparison of the total volume of wastewater treated daily in WWTP with the total volume of wastewater generated.

Parameter	Value, m^3/d	Ratio of influent to total raw wastewater
Average daily influent treated at the WWTP	353126	-41%
Maximum daily influent treated at the WWTP	405820	- 23%
Minimum daily influent treated at the WWTP	305811	-63%

4.7.2 REMOVAL EFFICIENCIES OF POLLUTANTS

Table 13 and Figure 8 show the changes of TSS and BOD_5 in the annual influent and the effluent of the WWTP from July/December 2004 to January/August 2010. As can be seen, influent TSS and BOD_5 concentrations entering and leaving the WWTP were relatively even during the study period. Generally, the concentrations of TSS, BOD_5, TP and TKN in the influent makes the wastewater to be characterized as moderately concentrated **(Table 13).** It is important to note that as is characteristic of domestic wastewater, the plant was characterized by strong variations in flow and concentration of organic load.

Table 13: Average, standard deviation (SD) and range of the water quality parameters of the WWTP from 2004 to 2010.

Parameters		Average	SD	Minimum	Maximum
Influent	BOD_5 (mg/L)	259	44	142	335
	COD (mg/L)	530	24	95	1187
	TSS (mg/L)	221	28	135	279
Effluent	BOD_5 (mg/L)	152	27	94	225
	COD (mg/L)	295	25	30	632
	TSS (mg/L)	87	13	62	131

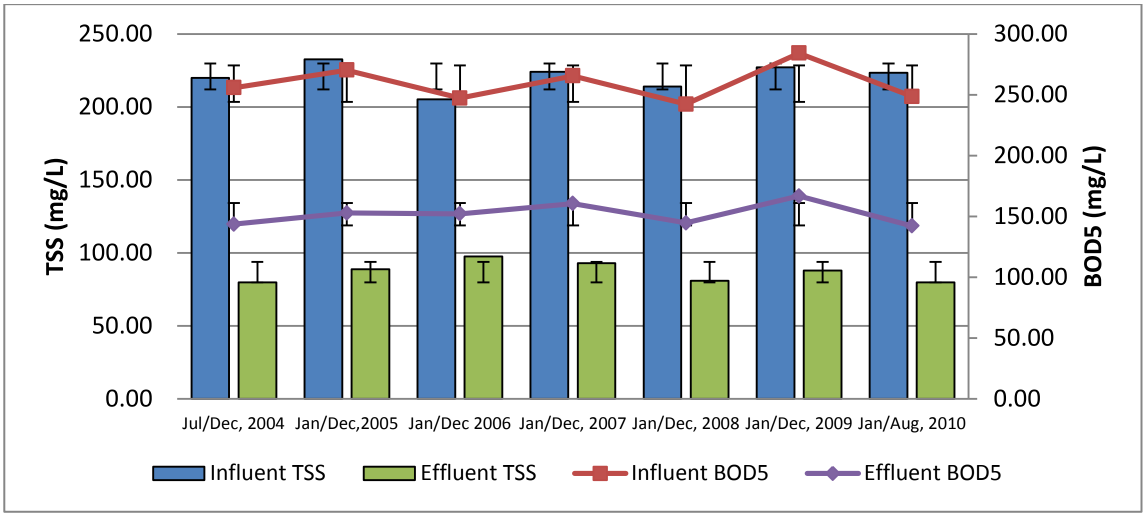


Figure 8: Comparison of the annual BOD_5 and TSS concentrations of the influent and the effluent.

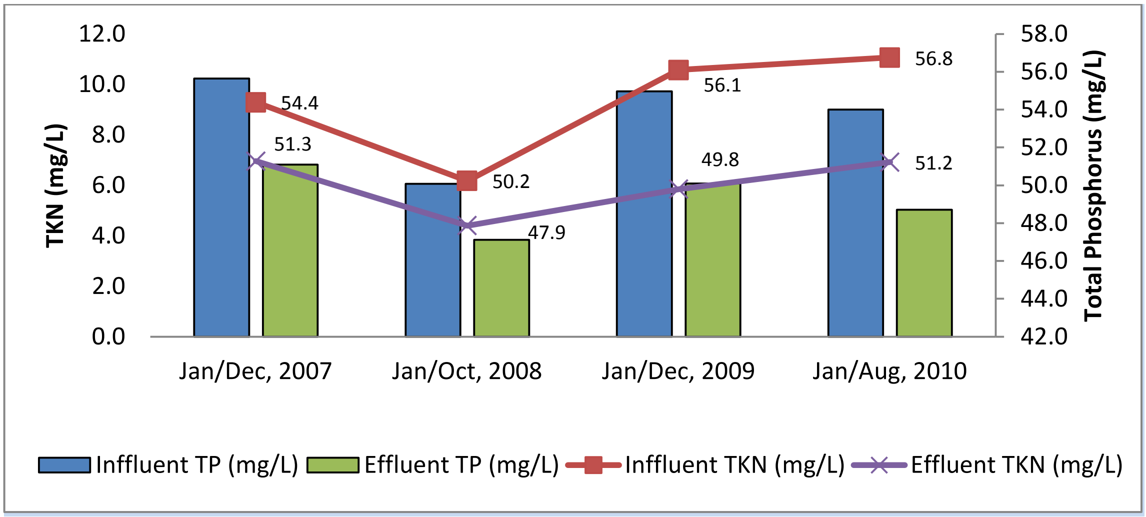


Figure 9: Comparison of the TP and TKN concentrations of the raw sewage and the treated wastewater.

Table 14: Load of pollutants entering and leaving the El Salitre WWTP and their removal efficiencies.

Parameters	Load In		Load Out		Removal Efficiency
	g/day	Kg/year	g/day	Kg/year	
TSS	77334575	212	30669327	84	60%
BOD	90753360	249	53583192	147	41%
COD	187156734	513	103993695	285	44%
TN	19068799	52	17626050	48	8%
TP	3107508	9	1903613	5	39%
Total Coliform	3189080118	8737	1567849626	4295	51%

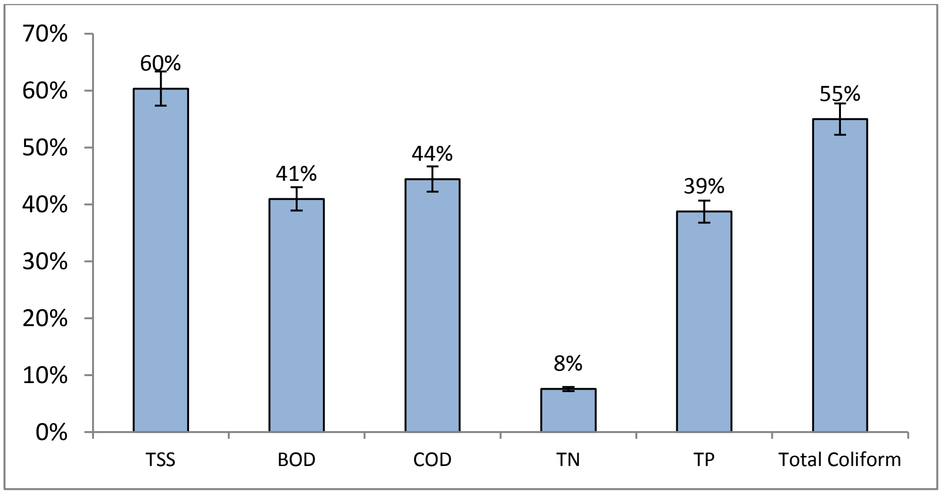


Figure 10: Removal efficiencies of pollutants at the El Salitre WWTP.

Table 15: Average concentration of physicochemical parameters in the influent generated at the El Salitre WWTP compared to typical values.

		Values from El Salitre WWTP			Typical concentration value[#]		
Parameters (mg/L)		Minimum	Maximum	Average	Weak	Average	Strong
Inffluent	**BOD_5**	142	335	259	110	220	400
	COD	95	1187	530	250	500	1000
	TSS	135	279	221	100	220	350
	TP	1.64	31.74	8.83	4	8	15
	TKN	11.0	85.40	54.36	20	40	85
	Total coliform				10^6-10^7	10^7-10^8	10^7-10^9

[#] SOURCE: Metcalf and Eddy, 1991

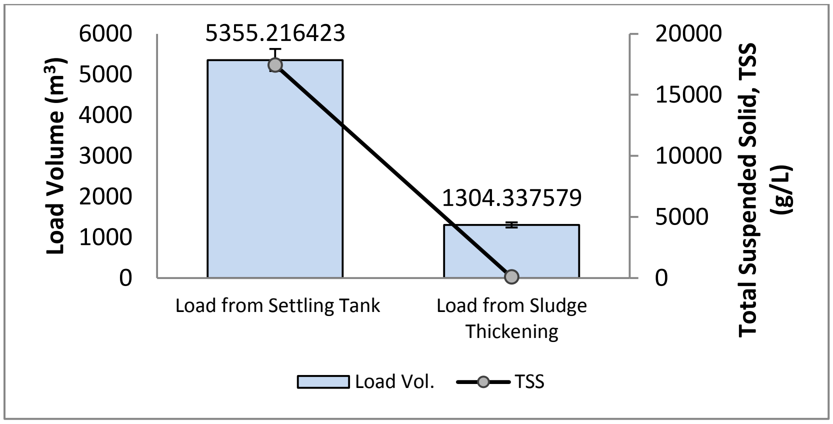


Figure 11: Comparison of the volume and TSS of load from the settling tank fed into the sludge thickening tank.

The inventory result analysis for functional sustainability of the plant (**see Table 14**) showed that the plants efficiencies for TSS and BOD_5 removal met the plants objectives (60% and 41%) but low with regards to chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and total coliform removal respectively (44%, 8%, 39%, 55%) as can be seem from **Figure 10** which is consistent with primary treatment processes.

On the other hand, results from data on monthly samples showed a decreasing capacity in the WWTP to remove pathogen (in the form of fecal coliform) evident in

Figure 12 with a removal efficiency of total and fecal coliform per volume of treated water of 51% and 44% (**see Tables 14 and 21**).

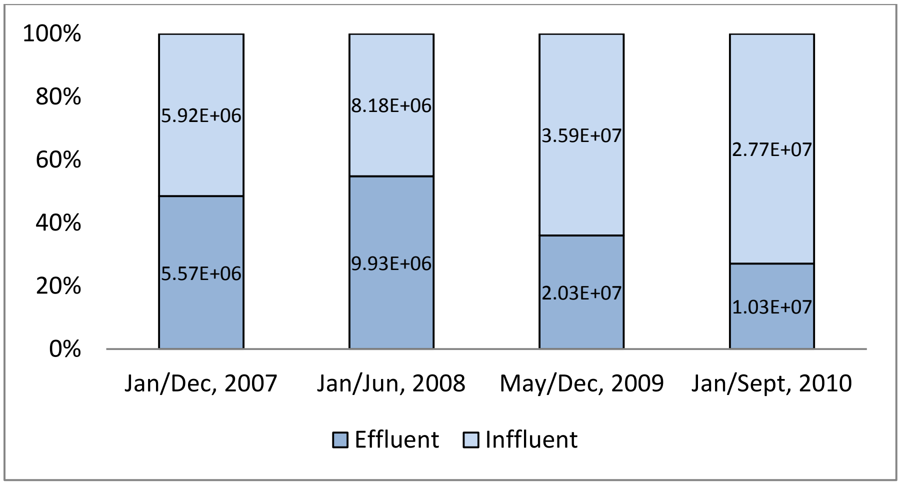


Figure 12: Comparison of the fecal coliform concentrations of the raw sewage and the treated wastewater.

4.7.3 ENERGY RECOVERED FROM THE WWTP

The bar screens (or bar racks) used to remove large objects during influent withdrawal and primary sedimentation, consumed more than half of the bulk of the energy required to run the WWTP. The air blowers used in supplying air to the sedimentation tanks consumed more than 35% of the total energy followed by the recirculation pump with 30% **(see Figure 13).**

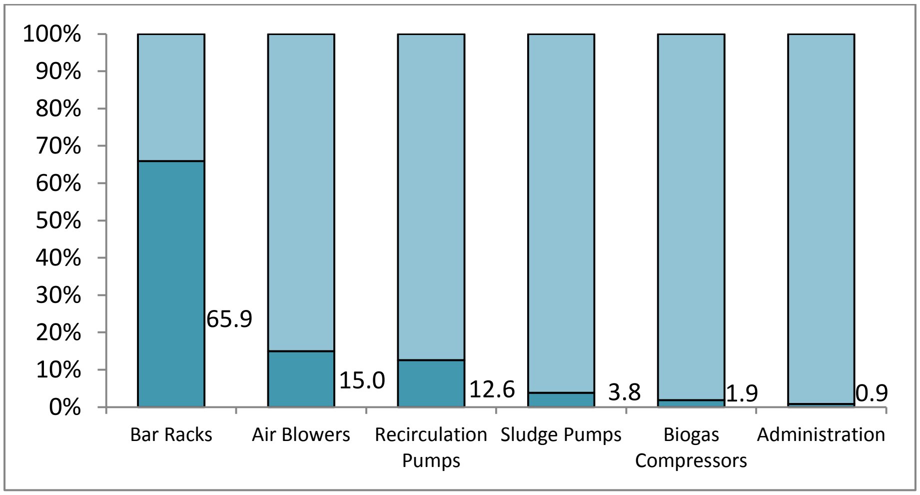


Figure 13: Energy consumption by operation units at the El Salitre WWTP.

The water line consumed the bulk of the total energy required for the operation of the WWTP used for wastewater extraction (78%) followed by the biogas line with an energy demand of about 15% of total energy. The sludge line, with an energy demand of about 6% was the least (see Table 16). On the whole, 7% of the total energy was needed for the treatment each volume of wastewater for the study period.

Table 16: Energy inventory for the defined treatment stages of the WWTP.

Treatment Stage	Energy Consumption (% of total WWTP)	kWh/m^3	Input (daily amount)	Output (daily amount)
Water Line				
Bar rack	65.89	0.042	353125 m^3 raw sewage	Solid residues disposed to landfill
Air Blowers	12.57	0.008	Air	Suspended matter and sand to landfill and concentrated biological sludge to digesters
Sludge Line				
Recirculation Pumps	3.81	0.002	Primary Sludge	
Sludge Pumps	1.90	0.001	Secondary Sludge	
Biogas Line				
Biogas Compressors	14.96	0.096	Biogas	Biogas, used partially for energy for the digesters, and the rest burned in torch
Administration				
Administration	0.87	0.001		

4.7.4 CHEMICAL USE

The evaluation of chemical consumption at the WWTP showed that ferric chloride ($FeCl_3$) contributed the bulk of the total chemical used, 94% (**see Table 17**). It was concluded that from the total chemical use per day per volume of treated wastewater value of 28.5 $gd^{-1}m^{-3}$, the chemical need for the plant's treatment process was relatively low. The low overall chemical consumption could be a result of the plant's reduced phosphorus (P) removal efficiency making environmental burden created by synthetic chemicals consumption to be was considered low.

Table 17: Average, standard deviation (SD) and design value of chemical consumption and at the El Salitre WWTP from 2005 to 2010.

	$FeCl_3$	**Polymer**		**Lime**		**Total chemical used**	
	Coagulant, ton/d	Pretreatment, ton/d	Dehydration, ton/d	Thickeners, ton/d	Digesters, ton/d	ton/d	g/d
Average	9.45	0.17	0.18	0.11	0.16	10.07	10067568
%	94%	3%		3%			
Design value	3.5	0.35	0.18				
SD	1.95	0.04	0.04	0.25	0.30	2.58	2575860

RATIO OF POLLUTANTS IN WASTEWATER

The wastewater pollutant ratios indicated that the influent load characteristics into the plant vary highly **(see Table 18).** The wide range of the influent COD/BOD_5 ratio (0.7 – 3.5) indicates that there were days when the plant received wastewater with organic matter difficult to treatment. However, the range of the COD/TN and VSS/VS ratio (8.6 – 13.9, 0.4 – 0.5) showed that on the general and favorable to denitrification indicating that the plant had considerably high fraction of organic matter in in form of suspended solids. The high COD/TP, BOD_5/TP and the COD/VSS ratios were also high (37.4 – 57.9, 3.9 – 12.9 and 2.2 – 3.2).

Table 18: Ratio of pollutants in the El Salitre influents and effluents of the WWTP.

Ratio	Influent		Effluent	
	Average	Range	Average	Range
COD/BOD$_5$	2.1	0.7 – 3.5	1.9	0.3 – 2.8
COD/TN	9.8	8.6 – 13.9	5.9	1.6 – 9.2
COD/TP	60	37.4 – 57.9	54.6	25 – 40
BOD$_5$/TN	4.8	3.9 – 12.9	3.0	3.3 – 4.9
BOD$_5$/TP	28.8	10.6 – 86.6	28.1	14 – 78
COD/VSS	3.4	2.2 – 3.2	4.5	1.6 – 4.7
VSS/TSS	0.5	0.4 – 0.5	0.3	0.3 – 0.4

4.7.5 LOAD OF POLLUTANTS ENTERING THE WWTP

Figure 14 Figure shows the TSS, BOD$_5$, COD, TN and TP average loads entering the WWTP in kilograms per inhabitant per day while **Figure 15** presents the average loads of the same parameters in the influent treated by the WWTP per drained area.

Table 19: Production of substances per inhabitant per day in Bogota.

Water	TSS	BOD$_5$	COD	TN	TP
#130 L/inh/day	32 g/inh/d	45 – 53 g/inh/d	84 g/inh/d	12 g/inh/d	2 g/inh/d
* 50–400 L/inh/d	-	15–80 g/inh/d	25–200 g/inh/d	1–15 g/inh/d	1 –3 g/inh/d

CAR, 2003 * Henze, 2002

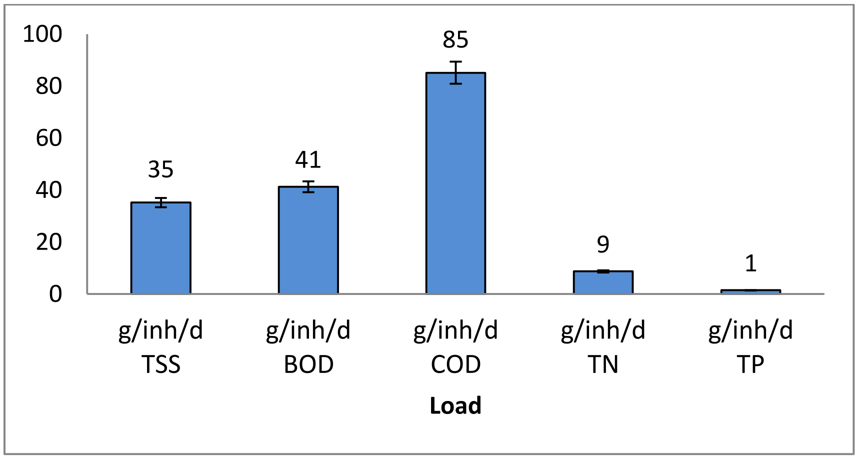


Figure 14: Average daily loads of TSS, BOD$_5$, COD, TN and TP entering the WWTP per inhabitant.

It was observed that the load in grams per inhabitant per day entering the WWTP was within the average value reported by the Regional Autonomous Corporations (Corporación Autónomas Regional CAR) for urban residual load (**see Table 19**). This implied that the influent is predominantly residual with little or no industrial discharges.

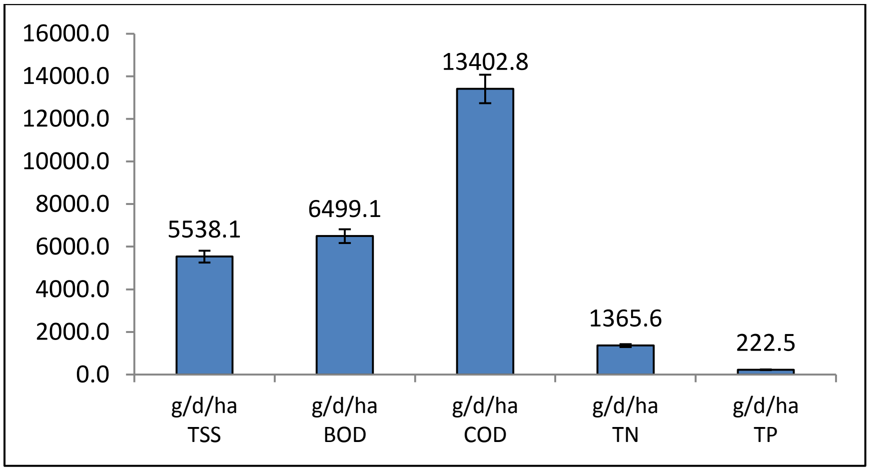


Figure 15: Average daily loads of TSS, BOD_5, COD, TN and TP entering the WWTP per drained area.

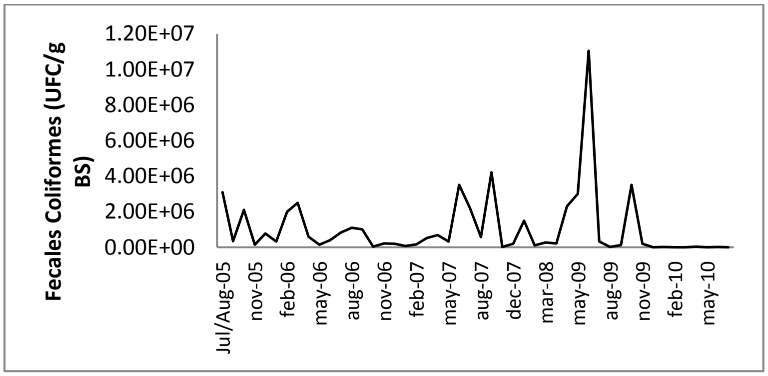


Figure 16: Tendency of fecal coliform concentration in the biosolid from the El Salitre WWTP.

4.7.6 ACTUAL PE AS A PERCENTAGE OF DESIGN PE

The plant was designed with an average population equivalent load from 2450000 inhabitants (i.e. 0.14 m^3/inh/d or 39 g BOD_5/inh/day) as compared to the actual value of 2200000 inhabitants (i.e. 0.16 m^3/inh/d; 41 g BOD_5/inh/day) (**see Table 20**). This indicates that the plant is working at 90% capacity with respect to the design value. Considering that the present population growth rate in Bogota is 1.48% (based on the 2005 Census value made by DANE) the plant will be working below capacity in the next 4 to 5 years.

Table 20: Design and actual value parameter for per capita load in the WWTP

	Design Value			Actual Value		
Parameters	BOD5	Load	per cápita load	BOD5	Load	per cápita load
Unit	mg/L	g BOD_5/d	g BOD_5/inh/d	mg/L	gBOD_5/d	g BOD_5/inh/d
Average	273.5	94521600	39	257	90753360	41
Peak	500	172800000	71	335	118297181	54
Minimum	150	51840000	21	142	50143880	23

4.7.7 CLIMATE AND ECOSYSTEM INFLUENCE ON SYSTEM PERFORMANCE

Figure 17 clearly shows that the ability of the plant to cope with influent flow fluctuations, climate and ecosystem influence on system performance was low. There was a relatively clear pattern between the monthly accumulated precipitation and the number of times the emergency diversion channel, used to control the influent volume treated by the WWTP, was opened. This was computed from monthly average data from 5 years.

The precipitation pattern coincides with the rainfall distribution where the months of January, February and December are the driest and the wet periods being April/May and October/November. The possibility to extend the system in capacity or with additional treatment within the present design and operational characteristics of the plant is considered low **(see Annex 9).**

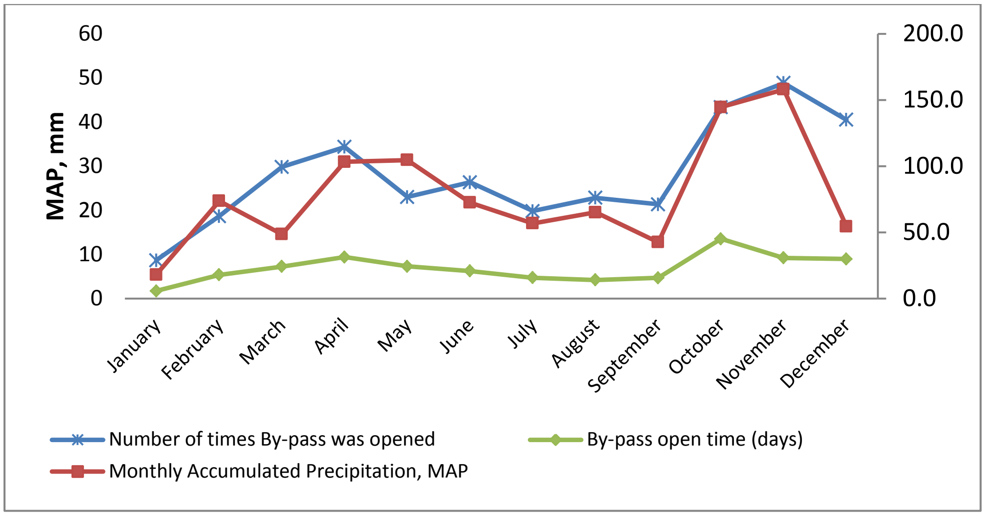


Figure 17: Relationship between precipitation and selected WWTP operation parameters (2006 – 2010).

4.7.8 NUMBER OF SYSTEM BREAKDOWN FOR MAINTENANCE

There is no recorded system breakdown from the information made available by the WWTP operators. However, the plant was periodically shut down for maintenance purposes. The plant is given a high score on the assessment scale.

Table 21: The inventory result analysis for functional sustainability of the El Salitre WWTP.

FUNCTIONAL	**Effectiveness**	Load of pollutants entering the WWTP	per inh. connected, g/inh/d	TSS	35	
				BOD	41	
				COD	85	
				TN	9	
				TP	1	
			per catchment area, g/d/ha	TSS	5538	
				BOD	6499	
				COD	13403	
				TN	1366	
				TP	223	
			per pop. Density, g/d/inh/ha	TSS	490864	
				BOD	576036	
				COD	1187935	
				TN	121035	
				TP	19724	
		Energy consumption per volume of treated WW, kWhm^{-3}, %			7	
		Total chemical use per day per volume of treated wastewater (gd^{-1}m^{-3})			29	
		Quantity of influent to WWTP as a percentage of total generated raw WW (%)			6	
	Efficiency	WWTP removal efficiencies of pollutants, %		TSS	60	
				BOD	41	
				COD	44	
				TN	8	
				TP	39	
				Total Coliform	55	
				Fecal Coliform	44	
		Net Energy recovered from the WWTP, kWh/inh/d (%)			73	
		Actual PE as a percentage of design PE (%)			90	
		Ratio of pollutants in WW		**Ratio**	**Inffluent**	**Effluent**
				COD/BOD	2.1	1.9
				COD/TN	9.8	5.9
				COD/TP	60	54.6
				BOD/TN	4.8	3
				BOD/TP	29.2	28
				COD/VSS	3.4	5
				VSS/SS	0.5	0.3
	A-F[#]	Climate and ecosystem influence on system performance			High	3
		No. of system breakdown for maintenance per day, No./day			Low	

[#] A-F means Adaptability and flexibility

4.8 ENVIRONMENTAL SUSTAINABILITY

4.8.1 RATIO OF POLLUTANTS IN EFFLUENT COMPARED TO EFFLUENT

Based on available data from the Bogota environmental observatory, the ratios were only calculated for TSS and BOD_5 **(see Annexes 11, 9 and 12)** based on total daily values of the pollutants into the water bodies. The values presented in **Table 22** show low self-purification capacity of the Salitre River. BOD_5 is the major indicator when compared to the relatively low value which could be attributed to the high removal efficiency of this indicator by the plant (60%). Regarding the higher TSS ratio as compared to the BOD_5 ratio from the plant to the Bogota River, it could be concluded that there exist other discharges into the river, possibly from other catchments (Fucha and Tunjuelo), agricultural and urban runoff. This occurs along the course of the river and the low removal efficiency of degradable organic materials with a high eutrophication potential of the receiving Bogota River. This is particularly true when considering that about 60% of the total wastewater generated within the El Salitre catchment area is discharge directly into the river without any form of treatment. The high values points out the fact that the Bogota River is considerably contaminated and as such reduces the aim of the Salitre WWTP to the Bogota River. Similarly, the ratio of the loads of the pollutant loads in the Bogota River compared to the Salitre River presented an equally high value.

Table 22: Ratio of measured total TSS and BOD5 discharged in the receiving waters.

		TSS[#]	**BOD_5**[#]
Total load in rivers (kg/day)	Salitre	173769	529899
	Bogotá	1382346	1372538
Total effluent load (kg/day)	WWTP	215323	374921
Ratio	Salitre-WWTP	0.81	1.41
	Bogotá-WWTP	6	4
	Bogotá- Salitre	8	3

[#] Total values were calculated from 2004 to 2010 (SOURCE: Bogota Environmental Observatory).

4.8.2 RATIO OF SOLIDS SENT TO LANDFILL COMPARED TO LAND APPLICATION

Comparison of the total solid generated (152667 kg/d) with the total solid removed from screening, pretreatment processes and primary settling stages sent to the landfill in the WWTP was very low. Only 3% (4354 kg/d) of the total solids was sent to the landfill while 97% (148313 kg/d) was generated as treated or stabilized sewage sludge. The biosolids produced at the plant has been used in the improvement of degraded soils and land initially in the Doña Juana Landfill and currently on the El Corzo site.

4.8.3 PHOSPHORUS AND NITROGEN RECYCLING THROUGH THE REUSE OF BIOSOLIDS

The potential recovery and reuse capacity of the WWTP for nitrogen and phosphorus, rather than their removal just for the aim of improving receiving water quality was evaluated. The quantity (kilogram) of nitrogen (N) and phosphorus (P) recycled through land application compared with total daily biosolids production by the plant were 1% and 3% respectively. This indicates that the phosphorus and nitrogen recycling through the reuse of biosolids was low. This signifies a low potential synthetic fertilizer displacement when applied to agricultural lands. Given that the removal efficiency in the effluent was 8% (1443 kg/d) and 39% (1204 kg/d) for phosphorus and nitrogen means that a bulk of the nutrients are lost as fugitive gases.

4.8.4 DISCHARGE OF SELECTED HEAVY METALS TO SOILS

This indicator criterion evaluates the environmental impact potential of the heavy metals present in the biosolid with the heavy metals concentration in the applied-soil in Predios El Corzo. **Table 23** shows the concentration and load rate of heavy metals in the biosolid and the soil application site while **Figure 18** illustrates the percentage of heavy metals in the biosolids generated daily from the WWTP. It was noticed that while the concentrations of some of the metals were low others were considerably high. The load of Copper (Cu), Zinc (Zn), Chromium (Cr), and lead (Pb) were substantially high - 12.4 kg/d, 15.4 kg/d, 26.7 kg/d and 156 kg. Notwithstanding, it is important to note that these values fall below the 2007 USEPA Regulation 40 CFR 503 for the use or disposal of sewage sludge for land application **(see Annex 15).**

Table 23: Comparing the amount of heavy metals found in the biosolid to the soil of the site of application.

Metal	**Value at biosolid application site - Predios El Corzo**		**Values of the biosolid from WWTP**	
	Conc. in Soil, mg/kg	Mixture (soil/biosolid), mg/kg	Conc. in biosolid, mg/kg	Load, kg/d
As	NA	NA	19	2.9
Cd	0	0.67	8	1.2
Cu	110	226.62	180	26.7
Cr	11	2.51	104	15.4
Hg	NA	NA	5	0.8
Ni	NA	NA	51	7.6
Pb	43	63.66	84	12.4
Zn	228	829.05	1053	156.2

The ratio of selected heavy metals in biosolid compared to applied soil showed that the concentration of Cr in the biosolid was more than nine time (9.4) to that in the soil while that of Zn was almost 5 times (4.6). Pb and Cu with 1.9 and 1.6 respectively **(see Table 24)** were the least. While considering the fact that not all the metals in the biosolid will be bio-available to crops it is pertinent to note that from heavy metal inventory perspective, the biosolid application on the soil might have negative environmental outcomes over time.

Table 24: The ratio of the selected heavy metals in biosolid to the concentration in the applied soil.

	Cu	Cr	Pb	Zn
Average, mg/kg	180.3	103.9	83.7	1053.4
Conc. in Soil, mg/kg	110	11	43	228.0
Ratio	1.6	9.4	1.9	4.6

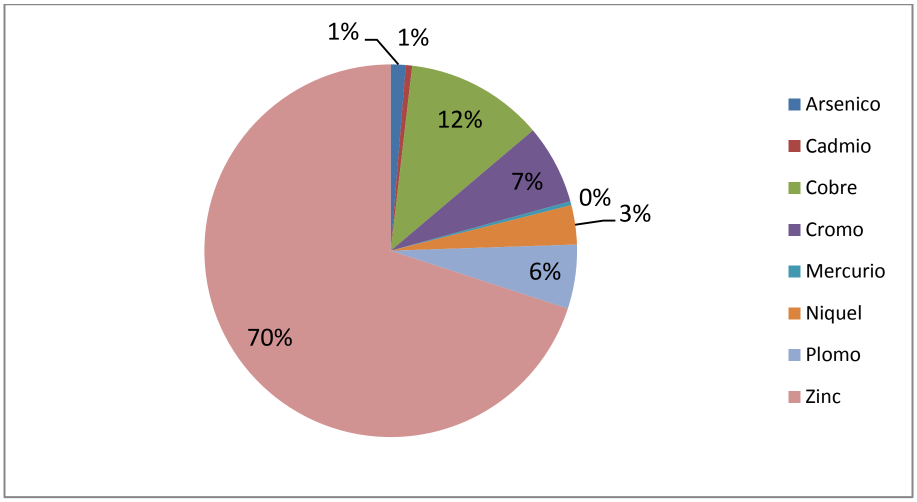


Figure 18: Percentage of heavy metals in the biosolids generated daily from the WWTP.

4.8.5 BIOGAS REUTILIZATION

The El Salitre WWTP is equipped with a gas collection system, where a portion of the generated gas is collected and flared while the other portion (30%) is used to produce the heat for the digesters. Data from the WWTP show that the biogas produced has an average characteristic composition of approximately 70.7% Methane (CH_4), 28.7% carbon dioxide (CO_2), 0.5% nitrogen (N_2) and 0.1% hydrogen sulfide (H_2S) and water.

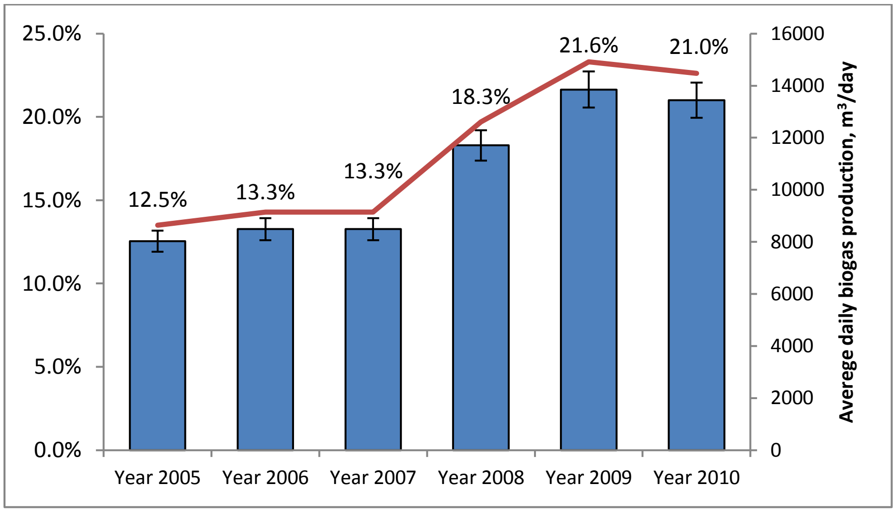


Figure 19: Percent average of total daily biogas production at the El Salitre WWTP during the study period.

Figure 19 above and **Table 25** show that the production of biogas is improving considerable with the total daily production increasing from about 12% in 2005 to 21 % in 2010. Average daily biogas production over the 6 years was determined to be 11956 m^3/day with about 3587 m^3/day recycled. Nonetheless, the percentage of the biogas reuse has remained the same implying that more of the biogas produced is flared implying an increase in CO_2 emission.

Table 25: Average daily biogas production from 2005 to 2010 at the El Salitre WWTP

Year	**Average daily production, m^3/day**
Year 2005	8643
Year 2006	9141
Year 2007	11918
Year 2008	12609
Year 2009	14915
Year 2010	14478

4.8.6 GREENHOUSE GAS (GHG) EMISSIONS

Figures 20 and 21 shows that the emission of methane (CH_4) from the WWTP treatment process and flaring was significantly high over the study period, 77% and

51% respectively. It is important to note, however, that this is consistent with the fact that WWTPs with anaerobic digesters generates methane-rich biogas.

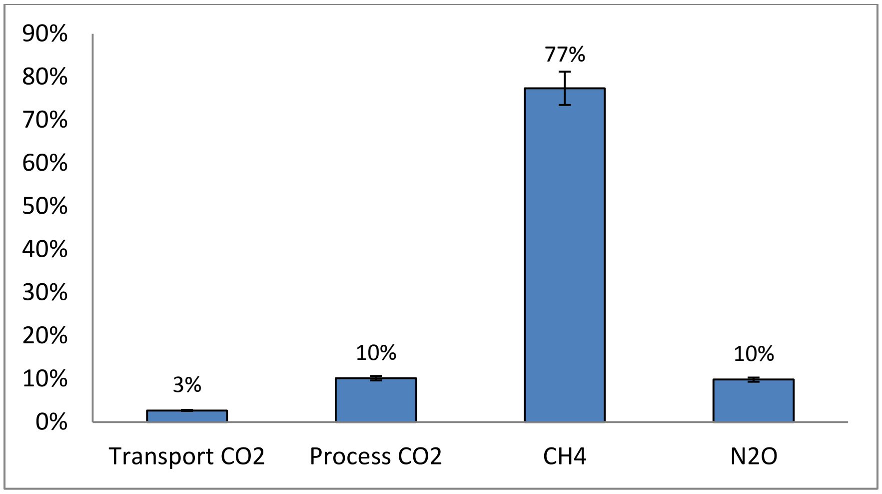


Figure 20: Comparison of the contribution of the selected greenhouse gas emissions from the WWTP process.

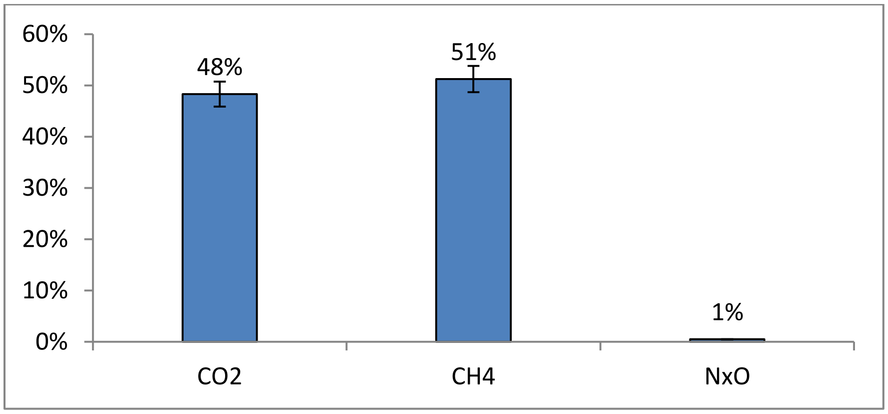


Figure 21: Percent CO_2 emissions from recovery at the El Salitre WWTP biogas flaring torch.

The total CO_2 emission from fuel use, process related emissions and emissions from recovery at the torch from the WWTP were calculated to be about 39740 kg CO_2-eq (**see Tables 26 and 27**). Contribution from process related emissions was the highest, 59%. Recovery and flaring at the torch and fuel use were 39% and 2% respectively. Estimations of the CO_2 emissions at the torch were made based on an average daily flow rate of 1.26 kg/m^3 (12.41 N/m^3) and an average daily volume of 8369 m^3 of biogas flared at the torch per day.

Table 26: Process greenhouse gas emissions from the El Salitre WWTP.

CO_2 Emission from fuel use				
Fuel types	**Basic Unit**	**Emission factor**		**kg CO2-eq**
	Value	**tCO_2/litre**	**CO_2 Released, t**	
Petrol, L/day	284	0.00222	0.63048	
Lubricants, L/day	7	0.00263	0.01841	
Other oil Producst, ton	4.38×10^{-7}	2.92	1.28×10^{-6}	
Sub-total			0.65	**649**
Process Related Greenhouse Gas Emissions				
GHG	**Value**	**Conversion factor**	**kg CO_2-eq**	
CO_2	2456	1	2456	
CH_4	893	21	18753	
N_2O	7.7	310	2380	
Sub-total				23589
Total kg CO_2-eq				**24238**

Table 27: CO_2 emissions from recovery by flaring the biogas produced at the torch.

Greenhouse gas (GHG)	**Percent Composition**	**Volume, m^3/day**	**Quantity recovered, kg/day**	**CO_2 emissions from recovery, kg CO2/day**
CO_2	70.70%	5916.9	7484.8	7484.8
CH_4	28.70%	2401.9	3038.4	7937.8
N_xO	0.50%	41.8	52.9	79.0
Total		8361	10576	15502

4.8.7 NUISANCE FROM ODOR, NOISE AND TRAFFIC

It is a well-known fact that regardless of how well designed and managed, WWTPs generate odor, and to a lesser degree noise and traffic from heavy duty trucks, resulting from the collection and operation of the plant. Odor is particularly considered an esthetic problem that usually evokes public involvement especially with mechanical systems (**see Annex 1)**. From a questionnaire survey of selected residents near the WWTP, it was observed that the pretreatment, sludge thickening and settling processing units presented the highest odor within the WWTP. From the analysis of historical records (2000 – 2009) favorable day and night odor states were obtained where odor varied from moderate to low in the neighborhoods near the WWTP **(see Figure 22).** Nevertheless, odor generated in the WWTP is a rejection factor in the surrounding population and as such the system used to monitor odors implemented in the WWTP El Salitre has served the need of evaluating the impact generated in the plant and the surrounding areas.

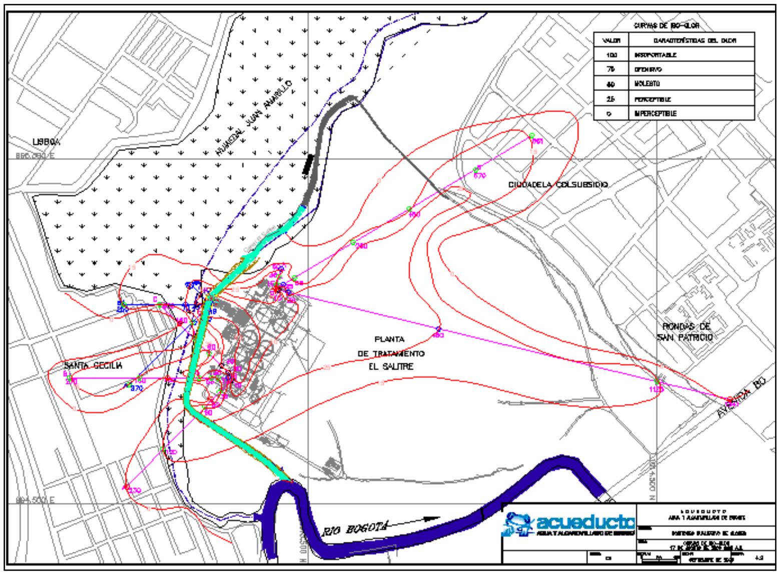


Figure 22: Iso-odor curves within and around the El Salitre WWTP (Source: EL Salitre WWTP Report, 2009)

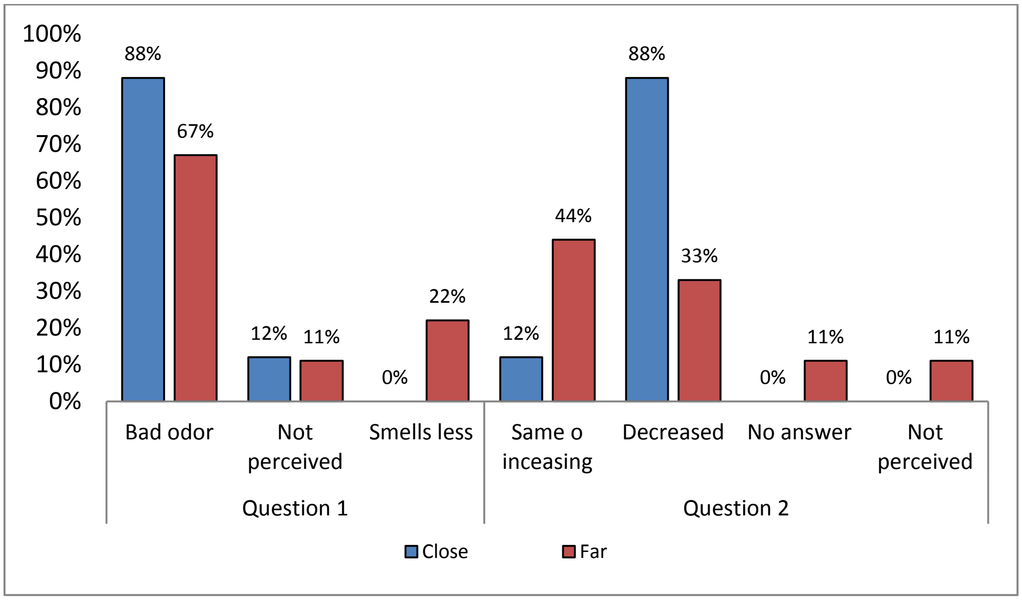


Figure 23: Results of questionnaire served to community residents aimed at assessing the perception of odor around the proximity of the WWTP (SOURCE: El Salitre WWTP Social Management Report, January/February 2009).

It is evident that that the source of the odor around the community area is still perceived to be from the plant rather than from the many different odor sources at distant areas **(see Figure 24).**

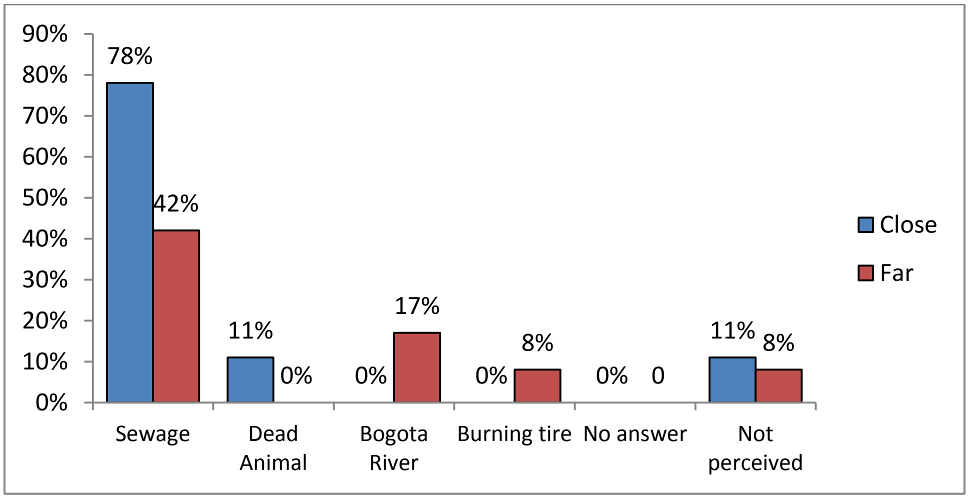


Figure 24: Comparing the odor from the WWTP with other reference odor sources (SOURCE: El Salitre WWTP Social Management Report, January/February 2009)

The community identified several possible causes of the perceived smell. Several of these causes are well adjusted to reality, but it is imperative to note that the sewer system was extensively perceived as responsible for the odor. 33% of community accrued the odor at remote areas to the IFT works as and no reference was made to it in the nearby area **(see Figure 25).**

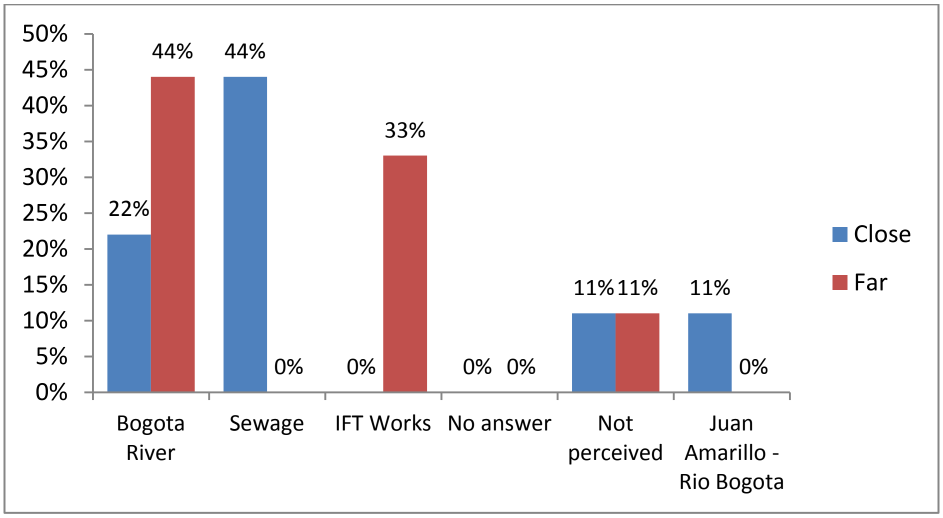


Figure 25: Comparison of the odor from the WWTP to other reference points close and/or far from the plant (SOURCE: El Salitre WWTP Social Management Report, January/February 2009)

4.8.8 PUBLIC HEALTH RISK (PHR)

Considering that the currently installed treatment system at the El Salitre WWTP corresponds to a primary treatment plant type, the public health risk of the effluent generated is relatively high. Pathogens removal (in terms of total coliform) of approximately 51% makes the threat from contact with the treated wastewater or sludge on the high side.

Table 28: The inventory result analysis for environmental sustainability of the El Salitre WWTP.

ENVIRONMENTAL	**Effluent Quality**	Ratio of pollutants in the receiving water compared to the WWTP effluent		TSS	0.81	
				BOD	1.14	
	Sludge Quality	Ratio of solids sent to landfill compared to land application.		Sludge to landfill - Kg/d	4354	97%
				Biosolid for land application - Kg/d	148313	
		Ratio of selected heavy metals in biosolid to applied soil.		Cu	1.6	
				Cr	9.4	
				Pb	1.9	
				Zn	4.6	
		P and N recycling through the reuse of biosolids compared with total daily biosolids production		Recycling of P, Kg/d	1923	
				Recycling of N, Kg/d	4314	
	Global Warming	Gas emission, Kg CO2-eq	Operation/Process	CO_2	2456	39740
				CH_4	18753	
				N_2O	2380	
			Transport/Fuel Use	CO_2	649	
			Flaring at torch	CO_2	15501	
		Gas reutilization		Recycled Biogas, m^3/day	3587	30%
				Flared Biogas, m^3/day	8369	70%
	Nuisance	Odor[θ]			Moderate	2
		Noise and Traffic[θ]			Low	1
	PHR[#]	Pathogens removal[θ] - %			51% Moderate	2

[#] PHR means Public Health Risk

[θ] Scale: High = 3, Moderate = 2, Low = 1

4.9 SOCIO-CULTURAL INDICATORS

4.9.1 COMMUNITY SIZE SERVED

The population size served evaluated against the WWTP treatment capacity showed a large municipal pollution loading. The high value indicated that the return of dissolved and solid residuals has a huge likelihood to create burden on the surrounding environment when considering the balance of nutrients and chemical fluxes in the urban environment.

4.9.2 WWTP FOOTPRINT COMPARED TO WASTEWATER TREATED

In densely urbanized areas, the plant foot print is considered a critical factor for treatment system selection. The low value of 0.28m^2/m^3 obtained **(see Table 31)** showed that the impact from land occupation for plant operations was minimal.

4.9.3 LABOR REQUIRED TO OPERATE THE WWTP

Based on the number of staff required to operate and maintain a wastewater facility with respect to plant capacity presented in **Annex 16g,** the El Salitre WWTP's average staff of 69 falls within the specified range (**see Table 31**). This also indicates that the plant potentially impacted the socio-economic developments of the immediate area through community employment. 33% of the work force comes from the surrounding community. Nonetheless, it was observed that for the last three years while the plant staff has increased the work for from the plant area has been constant. Since the plant is relatively located outside the catchment area, where the wastewater is generated, the social nuisance that odor might cause is greatly reduced **(see Table 29 and Figure 26).**

Table 29: Comparison of total staff and plant staff from WWTP Area of influence requirement at the El Salitre WWTP (2004 – 2010).

	Total plant staff	Plant staff from WWTP Area of influence	%
Administrative	12	3	17%
Operations	31	20	39%
Maintenance	20	8	28%
General service	6	4	37%
Total plant staff	69	34	33%

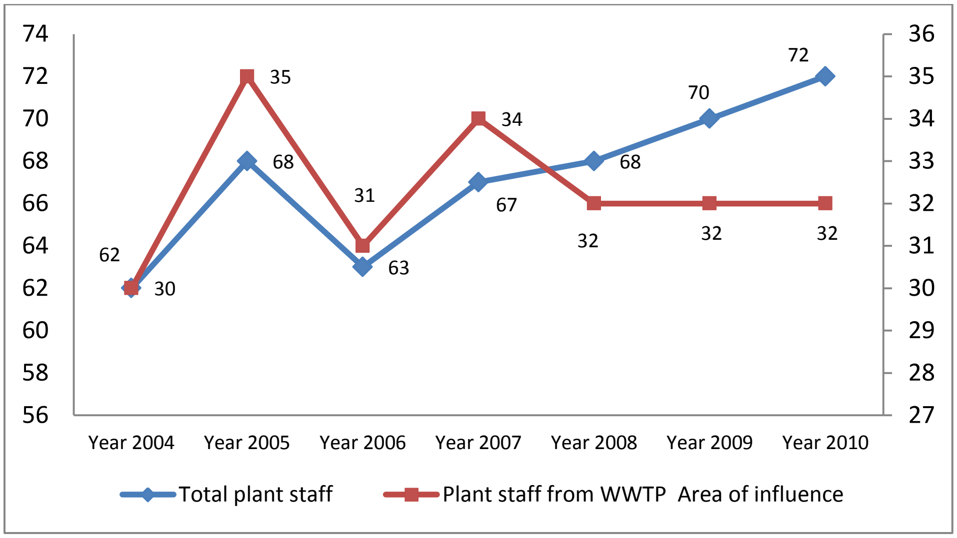


Figure 26: Graph showing total staff and plant staff from WWTP Area of influence requirement by area at the El Salitre WWTP (2004 – 2010).

4.9.4 COMMUNITY PARTICIPATION

This indicator criterion was evaluated by comparing the total population served to total visits to the WWTP and the number of employment generated in the WWTP community to the total staff. With respect to the stimulation of sustainable behavior by increasing the end-user's awareness and concern of the public to the sanitation plan it was found that approximately one out of 77 persons within the catchment area has visited the plant corresponding to 1% of the total catchment population (**Table 31**). It is important to note that the visits recorded by the plant are not limited, however, to residents within the catchment area. A total of about 29000 people (TV) ranging from college and high school students to communities respectively have visited the WWTP from 2004 to 2010 **(see Figure 27)**.

Table 30: Number of visits to the facilities of the WWTP.

	Total Visit from 2004 to 2010			
	Colleges	**High Schools**	**Institutions**	**Communities**
Number of visitants (persons) - NV	10673	14314	2077	1630
Percentage of total	37%	50%	7%	6%
Ratio of TV to NV	206	154	1059	1350

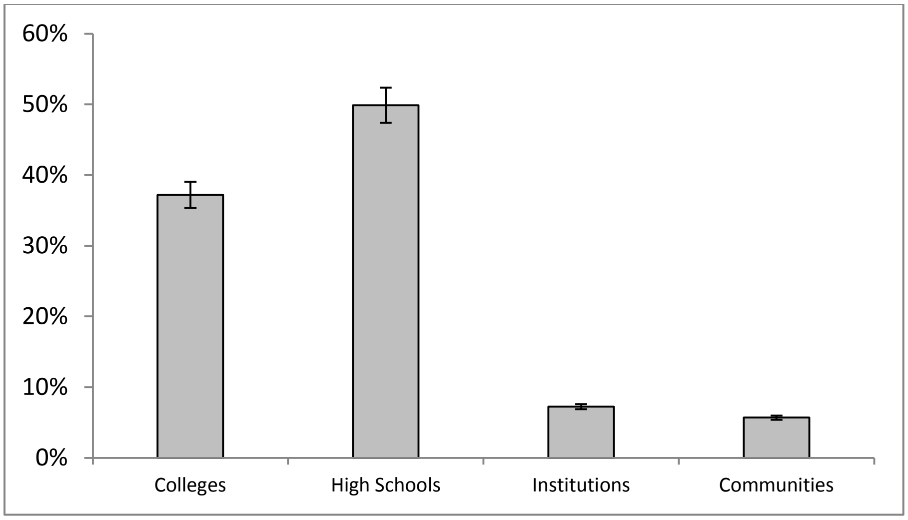


Figure 27: Visits to the El Salitre WWTP from 2004 – 2010

Table 31: The inventory result analysis for socio-cultural sustainability of the El Salitre WWTP.

SOCIO-CULTURAL	Community size served - Inh/m^3/d		6
	WWTP footprint compared to wastewater treated, m^2/m^3		0.28
	Aesthetics - Measured level of nuisance from odor		Medium = 2
	Labor required to operate the WWTP - Staff/m^3		69
	Expertise - Level of education	Professionals - Ratio of Total staff	
		Technical - Ratio of Total staff	
		Others - Ratio of Total staff	
	Community participation	Ratio of total population served to total visits to the WWTP	77
		Ratio of total staff to staff from the WWTP community	2

4.10 ECONOMIC INDICATORS

4.10.1 TOTAL COST PER VOLUME OF WASTEWATER TREATED

The total cost (TC), which includes maintenance and operational costs (OMC), pumping energy costs (EC) and chemicals cost (CC) per volume of wastewater treated per day revealed that about $167 Colombian pesos was spent for the treatment of each cubic meter of wastewater pumped into the WWTP per day which corresponds to about 0.1 US dollars **(see Table 32).** This value is considered to be on the low side given that conventional treatment processes may cost US$ 0.25-0.50 per cubic meter and that nonconventional options may cut costs by at least one-half.

Table 32: Cost per volume of wastewater treated per day at the WWTP and ratio of TC to UC.

	TC	OMC	EC	CC	UC	TC/UC
Average, \$/m^3/d	167.26	101.00	13.57	52.70	67.23	2.5
Minimum, \$/m^3/d	108.52	60.64	6.98	41.50	20.17	1.6
Maximum, \$/m^3/d	269.53	269.53	19.73	59.76	107.57	4.0

4.10.2 OPERATIONAL AND MAINTENANCE COST (OMC) PER VOLUME OF WASTEWATER TREATED

Operational and Maintenance Cost (OMC) are considered here to include personnel, sludge production, aeration energy and mixing energy, industrial security, spare parts and supplies, environmental costs and APS-Internal services. **Figure 29** below shows that 60% percent of total cost was incurred by the WWTP where the bulk came from the payment of allowances and operating costs associated with the wastewater treatment. Costs from environmental compliance and internal services follow with 16% respectively **(see Figure 28).** Analysis revealed that $101 Colombian pesos (0.3USD) was used for each volume of wastewater (cubic meter) treated at the plant per day.

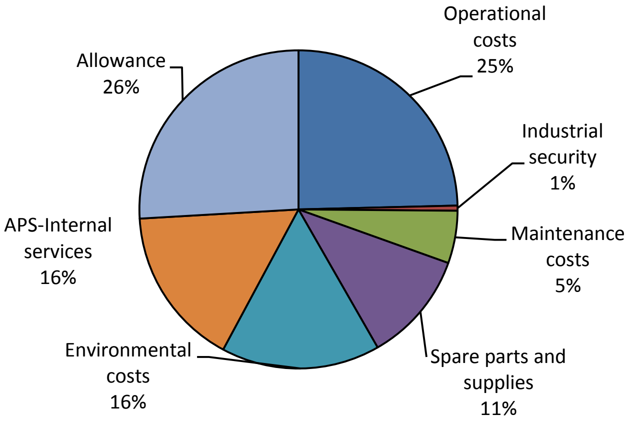


Figure 28: Percent relation of the operational and maintenance cost per volume of wastewater treated at the WWTP.

4.10.3 ENERGY COST PER VOLUME OF WASTEWATER TREATED

Figure 29 reveals that energy from pumping of the raw wastewater contributed about 8% of the plants total cost. This corresponds to about $14 per cubic meter of treated wastewater at the WWTP per day which is considered significant considering that other energy requirements from aeration and mixing were not included.

4.10.4 CHEMICALS COST PER VOLUME OF WASTEWATER TREATED

Given that the plant is a primary and chemically advanced treatment process the analysis of the cost implications of chemical use is important. The use of ferric chloride ($FeCl_3$) and anionic polymers for flocculation contributed 32% of the total energy used (**Figure 29**) which translates to about $53 Colombian pesos per cubic meter volume of wastewater treated at the plant per day.

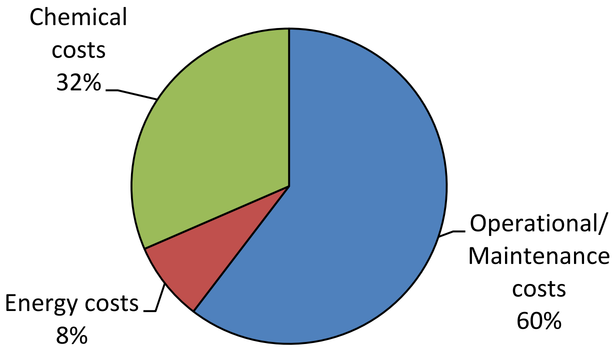


Figure 29: Contribution of operational and maintenance, chemical and energy costs to overall cost at the WWTP.

4.10.5 USER COST PER VOLUME OF WASTEWATER TREATED

The type of treatment technology, efficiency and the discharge option used is generally considered to determine wastewater treatment costs. The user cost (UC) of treatment of a cubic meter of wastewater within the El Salitre catchment area is $67.23 Colombian pesos. However, as shown in **Annex 14**, the subsidy system for low income residents makes the cost affordable to all users. However, the treatment cost for a cubic meter of wastewater by the plant is more than twice (2.5) the cost paid by users **(see Table 32).**

Table 33: The inventory result analysis for economic sustainability of the El Salitre WWTP.

ECONOMIC	Cost per volume of wastewater treated	Total Cost (TC) - $\$/m^3/d$	167.26
		Operational and Maintenance Cost (OMC) $\$/m^3/d$	101.00
		Energy cost (EC) - $\$/m^3/d$	13.57
		Chemical cost (CC) - $\$/m^3/d$	52.70
		User Cost - $/m3	67.23

4.11 OVERALL SUSTAINABILITY EVALUATION

To better appreciate the evaluated indicators on the overall sustainability of the wastewater system an alternative approach of presenting system sustainability was employed. After normalization, the individual results were displayed using a target or spider plot. Target plots, according to Muga and Mihelcic (2008) is a highly visual tool used for encapsulating sustainability in LCA and environmental product design and its appeal as a means of gauging sustainability is not difficult to understand. The plots have the advantage of making it easy to single out points that are far removed from the plot´s center that require improvements making it a decision-making tool in environmental management. This tool has been applied in this study to show the visual comparison between the functional, environmental, economic and socio-cultural indicators.

Table 34: Normalized value from the inventory data.

	Indicators	Indicator criteria	Normalized value
Functional	Effectiveness	Energy consumption per volume of treated WW	68
		Load of pollutants entering the WWTP	61
		Quantity of influent to WWTP as a ratio of total raw WW	46
		Total chemical use	36
	Efficiency	WWTP removal efficiencies of pollutants	36
		Net Energy recovered from the WWTP	39
		Actual PE as a percentage of design PE	22
		Ratio of pollutants in WW	75
	Adaptability/flexibility	Climate and ecosystem influence on system performance	56
		No. of system breakdown for maintenance per day	0
Environmental	Effluent Quality	Ratio of pollutants in the receiving water to the WWTP effluent	65
			55
	Sludge Quality	Ratio of solids sent to landfill compared to land application	13
		Ratio of selected heavy metals in biosolid to the applied soil	97
			93
			70
			69
		P and N recycling through the reuse of biosolids	48
			66
	Global Warming	Gas Emission	44
		Recyling of biogas	44
	Nuisance	Odor	50
		Noise and Traffic	0
	Public Health Risk	Pathogens removal	100
Economic	Cost per volume of WW treated	Operational and Maintenance Costs	81
		Energy Cost	48
		Chemical Cost	39
	User cost	User cost	46
Socio-cultural	WWTP footprint	Community size served	83
		WWTP footprint compared to wastewater treated	83
	Aesthetics	Aesthetics	50
	Required labor	Labor required to operate the WWTP	30
	Community participation	Ratio of total population served to total visits to the WWTP	50
		Ratio of total staff to staff from the WWTP community	23

The target plot shown in **Figure 30** displays the four SDIs dimensions, the indicator categories used to assess the sustainability of the WWTP and the impacts scale for the four dimensions.

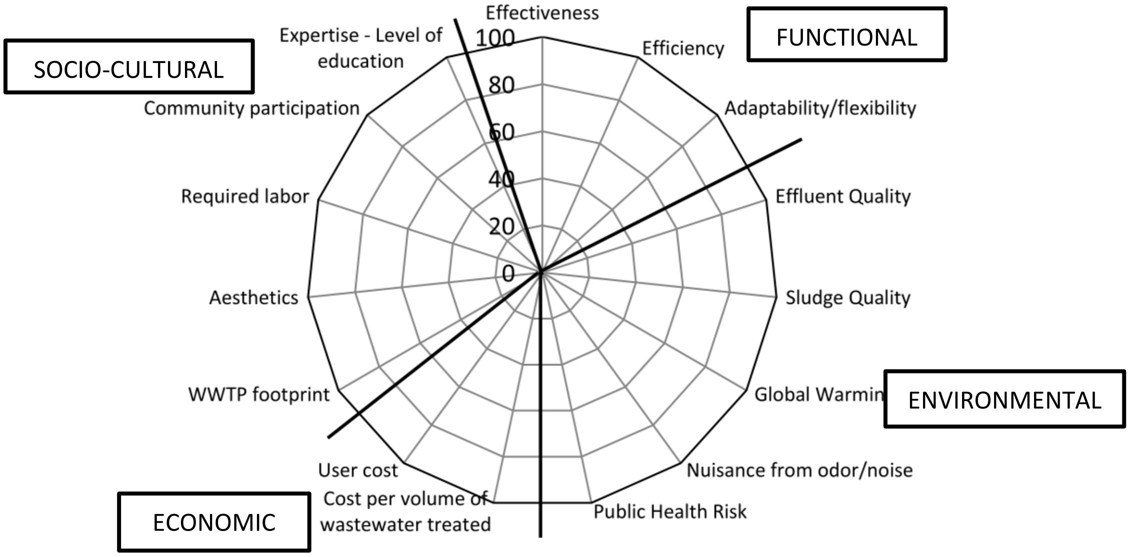


Figure 30: Target plot showing the four SDIs dimensions, the sustainability indicators used to assess the sustainability of the WWTP and the scale of impacts dimensions.

The impact scale from 0 to 100 indicates the tendency from a sustainable to unsustainable scenario. The conversion of the inventory data to the normalized target plot values can be found in **Annexes 16 a-j**. Target plot from normalized inventory data (**see Figure 31**) indicated that the plant has a varying degree of sustainability and adaptation capacity and improvements needs to be made in all the four selected indicator categories.

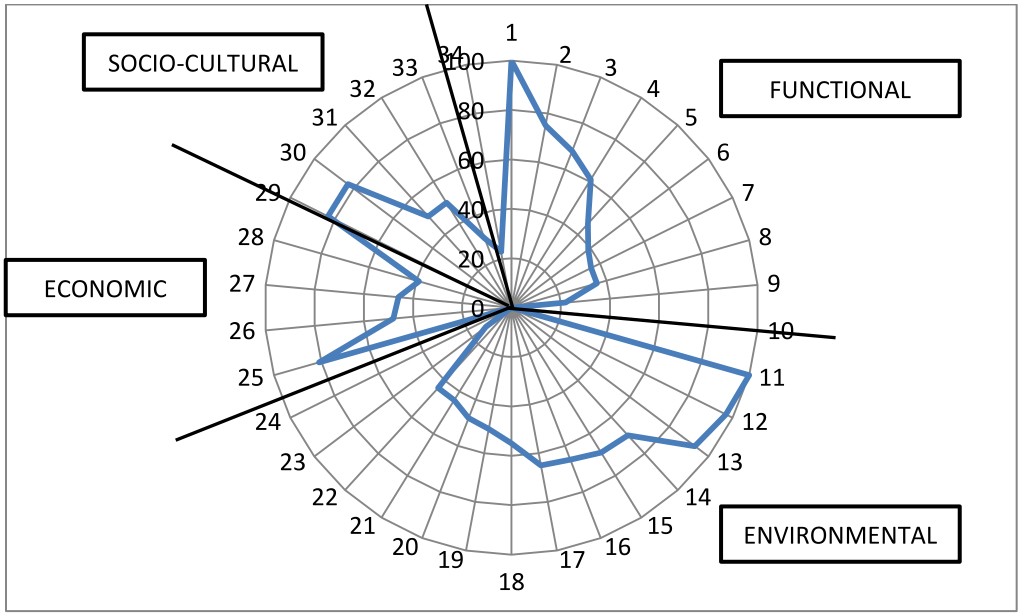


Figure 31: Target plot from the normalized inventory data of the El Salitre WWTP.

The least impact can be observed for functional and economic dimensions of the plant's operations while the greatest impact was from environmental dimension. The greatest environmental impact originated from the WWTP's low pathogen and heavy metal removal efficiency which is not characteristics of mechanical processes with primary treatment. Impact from phosphorus and nitrogen recycling and pollutant in effluents discharged into Bogota River were relatively high too. It is equally evident that very low environmental burden was created when comparing the solids sent to landfill to the stabilized biosolid for land application. The same was true for the burden caused by the noise and traffic from the operation of the WWTP and the reuse of the biogas generated.

In the same vein, the target plots shows that the functional sustainability with regards to the energy consumption per volume of treated wastewater was high and as such unsustainable. This can, however, be improved on if more or all of the biogas generated by the plant be recycled for electricity generated. Equally, the plot shows that the pollutants entering the plant fluctuated greatly as evidenced by the values obtained from the ratio of pollutants in influents entering the plant.

Climate and ecosystem influence on the functional performance of the plant was high more so given that the catchment area under study is characterized by high rainfall and prolonged precipitation. However, the total chemical use and the WWTP removal efficiencies of pollutants were low despite the fact that plant is a chemically assisted primary treatment process.

The operational and maintenance cost per volume of wastewater treated showed high values indicating that the economic impact of the operation of the plant was relatively unsustainable. When considering the economic burden created by the total cost incurred by the WWTP per cubic meter of wastewater treated was relatively unsustainable when compared to the cost the each user paid for the treatment of the same. The energy cost and chemical cost were relatively low representing low burden.

The community size served and the WWTP footprint compared to wastewater treated created burden on the socio-cultural dimension of the treatment process. This demonstrates that the capacity of the plant needs to be expanded and that the plant area can accommodate the expansion. The data also indicate that the presence of odor is seasonal or better put intermittent. This means that there is lower odor potential in lower temperature periods than days of higher temperature. The community participation measured by comparing the total population served to the total visits made to the WWTP and the total staff to the staff employed from the WWTP area of influence showed that this indicator was relatively moderate. It is important to note that the visits were not from residents within the catchment area.

Generally, the results suggest that the use of the selected sustainable development indicators (SDIs) is a good decision supporting tool which aims at providing opportunities for innovative processes and learning purposes for the much needed adaptability of the WWTP with regards the functional, environmental, economic and socio-cultural dimensions of a sustainable development. Again, the rating is a context-based decision that is subject to change with community, region and country.

5 IMPROVEMENT ANALYSIS

In line with the set objective of this study, an improvement analysis was carried out on the WWTP case study with the aim of improving the outcome of the selected SDIs through scenario analysis of the options for improvement. The impact of two scenario options was evaluated with particular focus on the first:

- Adaptation of management processes based on BMP.
- Adoption of appropriate technology intervention.

5.1 ADAPTATION OF MANAGEMENT PROCESSES BASED ON BMP

Improving the management of the system could improve the performance and efficiency of the system. According to the assessment of the current situation from the results obtained from the impact assessment, the indicators in **Table 36** were identified as needing improvement. This was based on a categorization of sustainability developed in line with sustainable goals assessment.

This sustainability assessment categorization framework was developed on the definition of SD which has been discuss earlier and on the basis of the goal of reducing the burden that urban WWTPs have in their immediate environment, both temporally and spatially, by adopting appropriate management procedures. The sustainability assessment categorization framework based on the normalization range of 0 to 100 is presented in **Table 35.**

Based on this framework, the identified indicators and indicator criteria were analyzed based on best management scenario to generate another plot diagram incorporating the recommendations to improve the WWTP system. Calculations were based on achieving a reduction or increase, as the case may be, in the range of the WWTP initial inventory data using the same normalization formula.

Table 35: The framework for the categorization of sustainability development assessment.

Sustainability assessment categorization		Description
0 – 25	Excellent	The operational impact and the burden created on global to local nature–society interactions by the indicator are sustainable.
26 – 50	Good	The operational effect and the burden produced on global to local nature–society interactions by the indicator are sustainable but can be improved on.
51 – 75	Acceptable	Indicator within this range show that the operational impact and the burden produced by the WWTP on global to local nature–society interactions are unsustainable and need to be improved on.
76 – 100	Undesirable	Indicator within this range indicates that the WWTP's operations and burden from its interactions with nature is unsustainable and needs immediate intervention.

Table 36: SDIs needing improvement with the system process.

	Indicators	Indicator criteria	Normalization	
			Actual	Improved
Undesirable	Efficiency	Ratio of pollutants in WW	75	48
	Sludge Quality	Ratio of Cr in biosolid to the applied soil	97	92
		Ratio of Zn in biosolid to the applied soil	93	24
	PHR	Pathogens removal	100	50
	Cost per volume of WW treated	Operational and Maintenance Costs	81	73
	WWTP footprint	Community size served	83	83
		WWTP footprint compared to wastewater treated	83	83
Acceptable	Effectiveness	Energy consumption per volume of treated WW	68	19
		Load of pollutants entering the WWTP	61	61
	Adaptability/flexibilidad	Climate and ecosystem influence on system performance	56	56
	Effluent Quality	Ratio of BOD_5 in the receiving water to the WWTP effluent.	65	33
		Ratio of COD in the receiving water to the WWTP effluent	55	14
	Sludge Quality	Ratio of Pb metals in biosolid to the applied soil.	70	39
		Ratio of Cu in biosolid to the applied soil	69	23
		P recycling through the reuse of biosolids	66	10

ENERGY CONSUMPTION PER VOLUME OF TREATED WW

Energy is a significant input both in terms of environmental and financial burden to urban wastewater management. The energy requirement for the treatment of each cubic meter of raw wastewater pumped into the WWTP was calculated to be high. Given that energy consumption in anaerobic digesters is electrical and thermal, and that energy input may be a function of sludge composition, operating and ambient conditions, the WWTP can make adequate use of the biogas to produce sufficient heat (thermal energy) for the WWTP needs. As such increasing the plant reutilization of the generated biogas from 30% to 50% would substantially reduce the gap in the range of energy required for heat generation for the digesters and also reduce the plants GHG emission as shown in the table below *(see Foley et al., 2010)*. This will equally reduce the GHG emission from the plant from the reduction in the biogas burned at the torch leading to higher energy recovery and lower residual digested sludge.

Table 37: Data form the improvement and normalization of biogas reutilization.

Parameters, m^3/day	**Actual Value**		**Improvement**	
	Average daily biogas production,	30% of energy recycled for thermal energy	40% of energy recycled for thermal energy	50% of energy recycled for thermal energy
Average	11955.8	3586.7	4782.3	5977.9
Maximum	18912.3	5673.7	5673.7	5673.7
Minimum	3180.2	954.1	954.1	954.1
Normalization		44	19	6

RATIO OF POLLUTANTS IN WW

Unfavorable nutrient ratios and high concentrations of individual substances reduce the degradation efficiency of biological wastewater treatment processes. Also, it has been described that that the N_2O emission and the performance of nitrogen removal from wastewater is highly dependent on the COD/TN ratio, which is one of the most significant parameters for N_2O emission control during wastewater treatment process (Wu et al., 2009). Optimization of nutrient ratios for wastewater treatment could be achieved by early recognition and continuous monitoring of critical parameters. This management scenario is essential in order to enable rapid corrective action when necessary. Only in this way can effluent compliance be within acceptable and stable range. This will ensure unnecessarily high or nutrient deficiencies in influents. Some examples of this management practice are:

- Bypassing primary treatment for carbon deficiency.
- Balancing the nutrient ratio either by the addition of N compounds (such as urea or turbid water from digester) during low-nitrogen influent or the addition of P compounds (such as phosphoric acid or phosphate fertilizers) during shortage of phosphorus.

The addition of phosphate fertilizer to the low-phosphorus content of the wastewater in the WWTP from 8.8mg/L to 60mg/L could lead to the scenario presented below.

Table 38: Data from the improvement and normalized of pollutants ratio in WW

Efficiency: Ratio of pollutants in WW			
	Actual value	**Improvement**	**Significance**
COD/BOD_5	2.1	2.1	Measure of the biodegradability of wastewater pollution load.
COD/TN	9.8	9.8	Measure of nitrogen removal capacity (nitrification)
COD/TP	60.2	8.8	Measures system performance for phosphorus removal
BOD_5/TN	4.8	4.8	Measures efficiency of denitrification process
BOD_5/TP	28.8	4.3	Measures wastewater oxygen requirement
COD/VSS	3.4	3.4	Approximates the amount of organic matter in the dissolved fraction of wastewater
VSS/SS	0.5	0.5	Approximates the amount of organic matter in the solid fraction of wastewater
Normalization	75	48	

In the same hand, the management practice will also bring about a significant improvement in the effluent pollutant range as demonstrated in the table below with a 30% simulation improvement in the peak and minimum values respectively.

Table 39: Improvement and normalization for comparing pollutant concentrations in the plant effluent to the receiving water bodies.

Parameters		Effluent load (kg/day)	
		BOD_5	TSS
Total load from WWTP	Average	374587	214685
	Improved Peak	721867.178	420240.284
	Improved Minimum	302084.003	198892.348
Total load in the Salitre River		529899	173769
Ratio	Salitre-Av. WWTP	1.4	0.8
	Salitre-Max. WWTP	0.7	0.4
	Salitre-Min. WWTP	1.8	0.9
Normalization		33	14

Table 40: Effects of nutrient deficiencies in the biological stage of wastewater treatment and possible corrective action.

Nutrient	Possible consequences	Corrective action
Carbon	• Profuse development of filamentous bacteria (sludge bulking and foam) • Insufficient denitrification	Bypass the primary treatment
Nitrogen	• High COD/TOC values in the influent • Filamentous bacteria	Balance the nutrient ratio
Phosphorus	• Increased COD/TOC values in the effluent • Filamentous bacteria	Balance the nutrient ratio

PATHOGENS REMOVAL

Bearing in mind that the El Salitre WWTP is a primary treatment process that applies chemical to aid pollutant removal efficiencies, pathogen removal is not necessarily a prime objective. However, the public health risk involved coupled with the fact that certain control practices could lead to a substantial reduction in effluent pathogen concentration is a favorable impact consideration. This is particularly true given that pathogen removal optimization can be brought about by the reduction in the suspended solids levels to the most practicably achievable levels for the system. Considering the improvement alternatives developed on previous indicator criteria this is an achievable goal to upgrading the pathogen removal efficiency of the plant. As such, this could considerable bring about a fall in the pathogenic presence in the effluent release from the WWTP to moderate (a scale 50 in the normalized data).

OPERATIONAL AND MAINTENANCE COSTS

The recycle flow rates or inventory variable (that is variable that control the proper performance of a WWTP system) has been defined to affect effluent pollutant concentrations and the plant's operating costs (Machado et al., 2009). As such, there is a trade-off between the operating costs of a WWTP and its effluent quality. Machado et al. (2009) determined that systematic design of control structure of effluent quality was determined to lower the operating costs and improve the effluent quality. The benefit brought about by the integrated process control to the water line was a 13% reduction on the operational cost of the case study. If this strategy is properly implemented to the operations of the El Salitre WWTP, similar trade-off could be achievement. The table below presents the impact of such management practice on the cost of the plant.

Table 41: Improvement and normalization for cost related data.

$/m^3/d	**TC**	**OMC**	**EC**	**CC**	**UC**	**TC/UC**
Average	167.26	101	13.57	52.7	67.23	2.5
Minimum,	94.41	52.76	6.07	36.11	17.55	1.4
Maximum,	234.49	234.49	17.17	51.99	93.59	3.5
Normalization	48	73	32	4	35	48

RATIO OF SELECTED HEAVY METALS IN BIOSOLID TO THE APPLIED SOIL

This study attempted to assess the environmental benefit of the use of the generated biosolid for land recuperation. While it is obvious that the concentration of some of the metals in the activated sludge is high (chromium and zinc) when compared to soil concentration, it should be noted that not all the metals will be bio-available. In line with Foley et al. (2010), the quantity of heavy metals in biosolids was fixed by the quantity of heavy metals in the influent raw wastewater. Therefore, there exists an opportunity to address this issue by strong source control.

One of such source control measures was reviewed by Wan Ngah and Hanafiah, (2007) where low-cost adsorbents obtained from chemically modified plant wastes can be used to replace for costly conventional methods of removing heavy metal ions from wastewater. Heavy metals such as Cr(III), Cu(II) and Zn(II) were able to be removed from wastewater using HCl treated carrot residues where maximum adsorption capacities were 45.09, 32.74 and 29.61 mg g^{-1} respectively (Nasernejad et al., 2005). Other plants waste common in Colombia whose adsorption capacities were investigated are banana stem chemically modified with formaldehyde, rice husk modified with tartaric acid, sugarcane bagasse modified with sodium bicarbonate, thylenediamine or Triethylenetetramine and sodium hydroxide modified saw dust from cedrus deodar wood. They could result in 31.85 – 139, 91.74 – 120.48 and 189 – 313 mg g^{-1} adsorption capacities for Cu (II), Pb (II) and Cd (II). (Wong et al., 2003b; Noeline et al., 2005; Junior et al., 2006; Memon et al., 2007). On the other hand, the use of biosorbents, such as cyanobacteria cultures of *N. muscorum*, *A. subcylindrica* was reported by El-Sheekh et al. (2004) to bring about considerable removal of heavy metals Cu, Co, Pb and Mn by 13–82, 12–34, 26–100 and 33–100%, respectively.

Another management option is the use of natural clays such as kaolin, bentonite to removal heavy metal ions from wastewaters instead of the traditional rapid mix method. This approach has been proven to be efficient and cost effective. One of such example is. This has the advantage of concentrating the metals in the clay for subsequent disposal in landfills rather than in the biosolid. As reported by Bedelean et al. (2010), bentonite can result in 80% to 100% removal of cadmium, lead, and chromium.

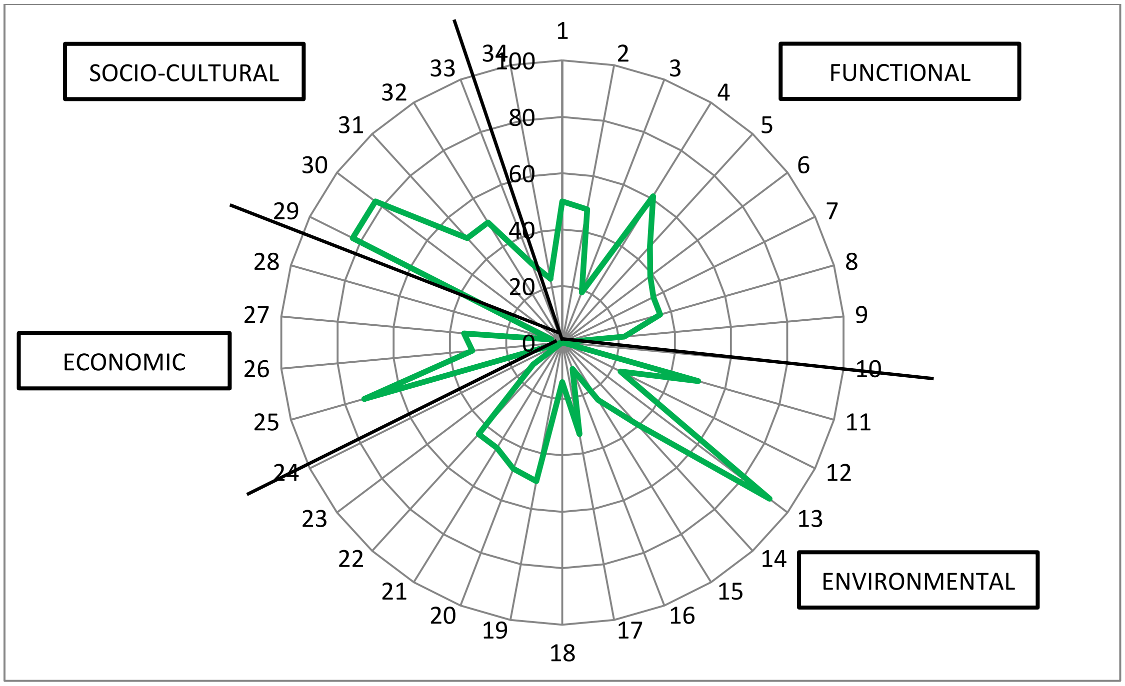
As such, if the gap in the range of the metal concentration is reduced by as much s 50%, value in Table 42 could be a possible outcome. As can be observed, the value of chromium remained high. In this case, chromium removal efficiency can only be improved on by adopting a source control management approach or better still by the adoption of a target chromium removal method.

Table 42: Improvement and normalized data of the heavy metals in the biosolid to that found in the soil where they are applied.

Value, mg/kg	Copper	Chromium	Lead	Zinc
Average	180.3	103.9	83.7	1053.4
Improved Maximum	224.7	1135.0	137.6	943.5
Improved Minimum	29.1	14.6	1.1	493.4
Conc. in Soil,	110	11	43	228.0
Ratio	1.6	9.4	1.9	4.6
	2.0	103.2	3.2	4.1
	0.3	1.3	0.0	2.2
Normalization	23	92	39	24

CLIMATE AND ECOSYSTEM INFLUENCE ON SYSTEM PERFORMANCE

The influence of climatic conditions on the functional performance of the WWTP is high given that the WWTP is located in a catchment area with high incidence of rainfall. Improvement to this indicator can only be achieved through the expansion of the WWTP which cannot be achieved in the nearest future. This is particularly true given that the watershed is an urban area with a characteristic high community size that also poses a problem. Consequently, there is no immediate improvement management practice to help accommodate the large material inputs and by extension the adaptability and flexibility of the plant.



Key: Indicator criteria not with the acceptable range.	
Point	**Indicator criteria**
4	Load of pollutants entering the WWT
13	Ratio of Cr in biosolid to the applied soil
25	OMC volume of wastewater treated
29	Community size served
30	WWTP footprint compared to wastewater treated

Figure 32: Target plot from the normalized inventory data with improvements on the indicator of sustainable interest of the El Salitre WWTP.

Figure 32 clearly shows that improvement based on best management practice (BMP) principles can contribute to making the plant and in general urban WWTP more sustainable. It is important to note that some management practices were not included into the improved set-up because of the complexity and technically difficulty of their implementation. Such management practices include plant expansion which will definitely reduce the impact created by the large community size and influence from climate conditions.

5.2 ADOPTION OF APPROPRIATE TECHNOLOGY INTERVENTION

In this category, evaluation of the possible impact of the proposed expansion of the plant as a technical means to improve the critical processes of the system was looked into. Upgrading treatment capacity and adaptation and optimization of the primary treatment to be secondary treatment with nitrogen and phosphorus removal units will greatly improve the impact from the plant.

This scenario would significantly cushion the climate and ecosystem influence on system performance as well as the removal of common pollutants (the remaining suspended and dissolved organic matter from the primary treatment), usually by a biological process. By extension, increase the quality of effluent which could be used for irrigation purposes. Impact from other indicator criteria such as pathogen and heavy metal removal efficiency would also be reduced and made more sustainable.

6 CONCLUSION

This research presents an approach to the assessment of the overall sustainability of the operational phase of an urban WWTP. The procedure involves the use of a set of selected SDIs incorporated into the LCA theoretical framework with particular emphasis on efficiency, overall performance and adaptability. The use of the El Salitre WWTP as a case study provided results that showed that the framework is apt in the assessment of the global sustainability of a WWTP and that alternative improvements can be identified apply appropriate best management practices (BMP) principles. This is particularly true given that the procedure overcomes the trade-off of most frameworks by showing the complexity of impacts as well as its simplification in order to make it understandable for all stakeholders involved in the decision making processes. The restriction of the traditional LCA approach to environmental-focused sustainability assessment is given a wider interpretation. Therefore, this research provides a multi-criteria aid to data management, visualization and technology improvement instead of alternative technology.

Understanding impact to mean the multiple and ripple effects that the function of any technological system has on the environmental, economic and socio-cultural aspects of ecological systems, on extensive literature review, a set of 4 SDI categories using 32 indicator criteria were developed to investigate the overall sustainability of the El Salitre WWTP: functional, environmental, economic and socio-cultural indicators. The inventory data for the case study was collected based on the first-order and second order processes of WWTPs. Temporal, spatial and life cycle boundaries were incorporated to provide data for the comparison of a large variety of integral solutions. A time perspective of six years, covering only the operational phase of the wastewater system, from the year 2004 to 2010 was used.

The review of existing information on the El Salitre watershed, one of the three (3) sub-catchment areas in the Bogota city, revealed that the El Salitre WWTP is the only such plant in the city. Increasing urbanization in the area (65%) creates pressure on water resources. The self-purification of water bodies in the area has been described to be limited. The El Salitre Plant, a primary/chemical treatment plant, with a capacity of $4ms^{-1}$ representing about 25% of the total wastewater generated in Bogotá and 41% of total wastewater discharged from the El Salitre catchment area, was built to contribute to the purification of the highly contaminated El Salitre effluent catchment discharged into the Bogota river. The Salitre River contributes 30% of the 90% pollution load that reaches the Bogota River. Applying the 32 indicator criteria was oriented to evaluate the performance of the plant with respect to the effluent from the plant.

As expected, the life cycle impact assessment revealed the overall sustainability of an urban wastewater treatment technology to be dependent on functional, environmental, economic and socio-cultural dimensions and further buttressing the fact that selection, adoption, and interpretation of indicators is influenced by an area's geographic, demographic characteristics and data availability. As typical of most mechanical WWTP, from the impact assessment of the El Salitre WWTP, the environmental dimension showed the most unsustainable performance followed by the functional dimension. The economic dimension presented the least unsustainability. Despite the fact that the plants TSS and BOD removal efficiencies met the plants objectives (60% and 41%) as stipulated in the wastewater management policy governing the functions of the plant, the target plot showed that the plant has a varying degree of sustainability and adaptation capacity and as such improvements needs to be made in all the 4 indicators categories.

Improvements based on BMP principles was applied on fifteen (15) indicator criteria (8 for environmental dimension, 4 for functional, 2 for socio-cultural dimension and 1 for economic dimension respectively) based on the developed sustainability assessment categorization. The implementation of the suggested improvement management practices will hugely move the processes of the WWTP to more sustainable scenarios. The improvements were made bearing in mind the need to adapt the treatment process to the effect of the varying influent characteristics entering the treatment system. Such improvement alternative included optimizing influent ratios, increasing recycled biogas and removal of heavy metals by chemically modified plant wastes.

Notwithstanding that the system boundary selected for this study was limited to the WWTP, the indicators used in this approach upholds the fact that the impact of non-sustainable wastewater management extends beyond the plants immediate area. The approach, therefore, makes it easy to identify the most problematic elements of a treatment system. The proposed improvements based on the adoption of best management practices (BMPs) within the plant processes promises to bridge the gap between the actual situations to a more sustainable alternative. Furthermore, this could be a new way to present monthly and yearly reports of a given WWTP because of its demonstrated capacity to show the varying degrees of a plant’s sustainability. In the light of this, the approach can be of huge advantage to right decision making as a feedback mechanism for continuous system improvement.

RECOMMENDATIONS

Although it is obvious that the framework proposed in this research presents a novel approach to the evaluation of the overall sustainability of urban wastewater plants, further study is needed into other indicator criteria which may be applied for WWTP sustainability. However, it is important to note that this study has set the bases for that. Further study should be carried out on the development, analysis and implementation of other possible indicators and indicator criteria that has the potential to promote representation of the overall sustainability of urban plant local operational conditions.

Expansion of the system boundary to include all second-order and third-order processes of urban WWTP process unit is recommended as this will contribute to a better understanding of the general sustainability evaluation of the developed assessment framework. The incorporation of aggregation (weighting) of criteria results could be estimated as an alternative although it is considered as not a satisfactory communication and discussion analysis option because it may lead to over-simplification of complex relationships and consequently misleading or lead to false representation.

Comparative studies of plants in urban areas in Colombia would also help to better understand local operational conditions that affect each plant as well as lay the ground for the much needed adaptive learning.

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ANNEX

Annex 1: Average monthly nutrient concentrations for the defined treatment stages at the El Salitre WWTP.

Parameters		Minimum	Maximum	Average
Influent	BOD_5 (mg/L)	141.91	334.68	259.06
	TSS (mg/L)	134.92	278.98	220.88
Treated wastewater	BOD_5 (mg/L)	94.17	225.03	151.80
	TSS (mg/L)	131.16	62.43	86.81
Load from Primary Settling Tank	Volume (m^3)	2945.37	7551.07	5355.22
	TSS (mg/L)	6003.83	59655.73	17446.08
	pH	6.73	7.17	6.93
Load from Sludge Thickening	Load Volume (m^3)	363.33	1756.11	1304.34
	TS (g/L)	61.32	144.86	83.71
	VS (g/L)	27.73	95.06	47.24
	pH	5.96	7.11	6.47
Digester Load	Volume of lad to digester (m^3)	351.56	1473.24	1092.10
	TS of Load (g/L)	61.07	103.88	81.25
	VS of Load (g/L)	21.41	45.08	35.89
	Alkalinity (mg $CaCO_3$/L)	1950.32	3161.19	2594.52
	pH	7.2	7.6	7.4
Biosolid Characteristics	Volume of Biosolid (m^3/day)	45.54	213,93	144,39
	Humidity (%)	63.89	93.46	70.80
	Dryness (%)	23.76	42.92	32.68
	TS (g/L)	7.39	444530,89	259639.99
	VS (g/L)	2498.52	207559,36	128175.35
	Density (g/cm^3)	0.74	1.31	0.89

Annex 2: Average flow rate of raw sewage and treated wastewater at the El Salitre WWTP.

Date	Flow rate (m^3/year)	
	Treated Wastewater	**Extracted Raw Wastewater**
Jul/Dec., 2004	60958090	69973090
Jan/Dec, 2005	123549360	124731670
Jan/Dec, 2006	138322095	138742470
Jan/Dec, 2007	130319407	131154840
Jan/Dec, 2008	128069158	128686592
Jan/Dec, 2009	123462542	124059620
Jan/Dec, 2010	96718842	96125720

Annex 3: Average volumetric flow rate of solids generated at the El Salitre WWTP.

Parameters	Minimum	Maximum	Average
Volumetric flow of Biosolid (kg/m^3.day)	0,10	0,63	0,42
Volumetric flow of Fine residues (g/m^3.day)	0,00	7,87	2,50
Volumetric flow of Coarse residues (g/m^3.day)	0,75	6,90	2,90
Volumetric flow of Sand (g/m^3.day)	0,06	5,40	1,48
Volumetric flow of Fat (g/m^3.day)	1,86	9,00	5,49

Annex 4: Average chemical doses used at the El Salitre WWTP.

Year	Chemical Doses		
	$FeCl_3$ (g/m^3)	Polymer	
		Anionic (g/m^3)	Cationic (Kg/ton MS)
Jul/Dec, 2004	31.66	0.63	0.00
Jan/Dec,2005	29.69	0.59	0.00
Jan/Dec 2006	24.41	0.50	3.82
Jan/Dec, 2007	28.67	0.47	4.30
Jan/Dec, 2008	28.63	0.47	3.99
Jan/Dec, 2009	27.66	0.49	4.45
Jan/Sept, 2010	23.68	0.41	4.16

Annex 5: Average dry weight concentration of heavy metals in the biosolid generated at the El Salitre WWTP.

Biosolid from EL Salitre WWTP				US EPA Standard[‡]		EU Standard*	
Parameters (mg/kg)	Minimum	Maximum	Average	CCL for all biosolids applied to land[†]	PC limits[†]	Limit value in soil	Limit value in Biosolids
Arsenic (As)	0,170	76,2	19,4	75	41		
Cadmium (Cd)	1,240	31,2	8,3	85	39	1-3	20-40
Copper (Cu)	58,127	449,4	180,3	4300	1500	50-140	1000-1750
Chromium (Cr)	29,100	2270,0	103,9	3000	1200	-	-
Mercury (Hg)	0,030	35,0	5,1	57	17	1-1.5	16-25
Nickel	8,7	540,7	51,2	420	420	30-75	300-400
Lead (Pb)	2,3	275,1	83,7	840	300	50-300	750-1200
Zinc (Zn)	278,7	1887,0	1053,4	7500	2800	150-300	2500-4000

[†] Ceiling concentration limits, CCL and applies to all biosoilds that are land applied.
[#] Pollutant concentration, PC for bulk and bagged biosolids.
[‡] SOURCE: Shun, 2007
* SOURCE: Kiely, 1999

Annex 6: Average concentration of physicochemical parameters in the biosolid generated at the El Salitre WWTP.

Parameters (mg/kg)	**Minimum**	**Maximum**	**Average**
Total Solid (TS)	255192.00	387104.00	312466.15
Total Nitrogen (TN)	3165.00	52692.00	28865.75
Nitrate	0.57	82.80	22.35
Nitrite	0.02	21.30	1.63
Total Phosphorus (TP)	64.65	37739.00	12636.76
pH	6.6	8.3	7.6

Annex 7: Average concentration of physicochemical parameters in the influent generated at the El Salitre WWTP compared to typical values.

Parameters (mg/L)		**Values from El Salitre WWTP**			**Typical concentration value**[#]		
		Minimum	Maximum	Average	Weak	Average	Strong
Inffluent	**BOD_5**	335	142	259	110	220	400
	COD	1187	95	530	250	500	1000
	TSS	279	135	221	100	220	350
	TP	1.64	31.74	8.75	4	8	15
	Nitrates	0.02	1.87	0.25	0	0	0
	Nitrites	0.003	0.26	0.02	0	0	0
	TKN	11.0	85.40	54.36	20	40	85
	Total coliform				10^6-10^7	10^7-10^8	10^7-10^9

[#] SOURCE: Metcalf and Eddy, 1995

Annex 8: Average concentration of physicochemical parameters in the effluent generated at the El Salitre WWTP.

Parameters (mg/L)		**Minimum**	**Maximum**	**Average**
Effluent	**TP**	1.160	16.08	5.44
	Nitrates	0.01	0.76	0.19
	Nitrites	0.001	0.166	0.013
	TKN	19.3	69.2	50.04

Annex 9: Average monthly data for MAP, number of times the emergency diversion channel was opened and emergency diversion channel open time.

Month	Number of times emergency diversion channel was opened	Monthly Accumulated Precipitation, MAP	Emergency diversion channel open time (days)
January	9	18.0	1.7
February	19	73.6	5.4
March	30	48.5	7.3
April	34	103.2	9.4
May	23	104.5	7.3
June	26	72.5	6.2
July	20	56.7	4.7
August	23	65.1	4.2
September	21	42.5	4.7
October	43	139.5	13.5
November	49	158.0	9.2
December	41	54.4	9.0

Annex 10: Odor potential for typical unit processes in a wastewater treatment plant (adapted from Muga and Mihelcic, 2008).

Unit process	Odor potential
Treatment plant	
Primary Clarifiers	High
Trickling filters	High
Aeration	Low
Lagoons	Moderate
Terrestrial	Low/Moderate
Secondary clarifiers	Low/Moderate
Sludge handling	
Thickening	High
Aerobic digestion	Moderate
Sludge storage basins	Moderate/High
Dewatering	High

Annex 11: Effluent load of annual average TSS and BOD_5 measured at the El Salitre WWTP

Year	Volume of Effluent (m^3/day)	TSS (mg/L)	BOD_5 (mg/L)	TSS (kg/day)	BOD_5 (kg/day)
Jan/Dec., 2004	351104	80	144	28088	50559

Jan/Dec, 2005	338491	89	153	30126	51789
Jan/Dec, 2006	378965	98	152	37139	57603
Jan/Dec, 2007	357039	93	161	33205	57483
Jan/Dec, 2008	349868	81	145	28339	50731
Jan/Dec, 2009	337975	89	167	30080	56442
Jan/Dec, 2010	354329	80	142	28346	50315

Annex 12: Ratio of total suspended solids (TSS) discharged in the receiving waters.

	Salitre River#		**Bogota River#**		**El Salitre WWTP**	**Ratio**		
Year	ton/year	kg/day	ton/year	kg/day	kg/day	Salitre-WWTP	Bogota-WWTP	Salitre-Bogota
2003	11347	31088	101657	278512				0.11
2004	37328	102268	136788	374762	28088	3.64	13	0.27
2005					30126			
2006	4280	11726	83156	227825	37139	0.32	6	0.05
2007	3375.6	9248	79207.5	217007	33205	0.28	7	0.04
2008	2710	7425	49215	134836	28339	0.26	5	0.06
2009	6398.7	17531	62336.7	170785	30080	0.58	6	0.10
2010	9333.5	25571	93853	257132	28346	0.90	9	0.10

Annex 13: Ratio of biological oxygen demand (BOD_5) discharged in the receiving waters.

	Salitre River#		**Bogota River#**		**El Salitre WWTP**	**Ratio**		
Year	ton/year	kg/day	ton/year	kg/day	kg/day	Salitre-WWTP	Bogota-WWTP	Salitre-Bogota
2003	55052	150828	110639	303121				0.50
2004	38299	104927	100034	274066	50559	2.08	5.4	0.38
2005					51789			
2006	16339	44763	109691	300523	57603	0.78	5.2	0.15
2007	31409	86052	80259	219888	57483	1.50	3.8	0.39
2008	35350	96850	49983	136940	50731	1.91	2.7	0.71
2009	36008	98653	85993	235597	56442	1.75	4.2	0.42
2010	36008	98653	75016	205524	50315	1.96	4.1	0.48

Bogotá Environmental Observatory, Secretaria Distrital de Ambiente.

Annex 14: User cost and subsidy for the treatment of a cubic meter of wastewater in Colombia.

Income stratus	**Subsidy (-) or contribution factor**	**Cost, $/m3**

1	-70%	20.17
2	-40%	40.34
3	-12%	59.16
4	0%	67.23
5	50%	100.85
6	60%	107.57
Industrial	43%	96.14
Commercial	50%	100.85
Official	0%	67.23

Annex 15: Comparing the concentration of heavy metal in the biosolid with standard values.

Metals	Conc. in biosolid, mg/kg	Excellent Biosolid Quality** (mg/kg dry weight)
As	19	41
Cd	8	39
Cu	180	1500
Cr	104	Not regulated
Hg	5	17
Ni	51	420
Pb	84	300
Zn	1053	2800

**USEPA Standard Regulation 40 CFR 503 for the use or disposal of sewage sludge (2007).

Annex 16a: Normalization of gas emission data.

CO$_2$ Emission from fuel use					
Fuel types		**Basic Unit**	**Emission factor**		**kg CO2-eq**
		Value	**tCO$_2$/litre**	**CO$_2$ Released, t**	
Petrol, L/day	Average	284	0.00222	0.63048	
	Minimum	52	0.00222	0.11544	
	Maximum	863	0.00222	1.91586	
Lubricants, L/day		7	0.00263	0.01841	
Other oil Producst, ton		4.38×10^{-7}	2.92	1.28×10^{-6}	
Total	**Average**			0.65	**649**
	Minimum			0.76	764
	Maximum			3.33	3329
Process Related Greenhouse Gas Emissions					
GHG		**Value**	**Conversion factor**	**kg CO$_2$-eq**	
CO$_2$	**Average**	2456	1	2456	
	Minimum	1357	1	1357	

	Peak	3201	1	3201	
CH_4	**Average**	893	21	18753	
	Minimum	493	21	10362	
	Peak	1164	21	24445	
N_2O	**Average**	7.7	310	2380	
	Minimum	1.6	310	482	
	Peak	12.1	310	3739	
Total	**Average**				23589
	Minimum				12200
	Maximum				31386
Total kg CO_2-eq	**Average**				**24238**
	Minimum				12965
	Maximum				34715

Annex 16b: Normalization of data from CO_2 emissions from recovery from flaring the biogas generated at the plant.

Greenhouse gas (GHG)		Percent Composition	Volume, m^3/day	Flow rate, Kg/m^3	Quantity recovered, kg/day	CO_2 emissions from recovery, kg CO_2/day
CO_2	Average	70.7%	5916.90	1.26	7485	7485
	Maximum		9359.68	1.47	13741	13741
	Minimum		1573.89	0.89	1407	1407
CH_4	Average	28.7%	2401.91	1.26	3038	7938
	Maximum		3799.47	1.47	5578	14572
	Minimum		638.91	0.89	571	1492
N_xO	Average	0.5%	41.85	1.26	53	79
	Maximum		66.19	1.47	97	145
	Minimum		11.13	0.89	10	15
Total	**Average**					**15502**
	Maximum					**28458**
	Minimum					**2914**

Annex 16c: Normalization data for biosolid generated to sludge sent to the landfill.

	Biosolid for land application		**Sludge sent to landfill**	
	Flow rate, kg/m3	Load, kg/d	g/m3	Load, kg/d
Average	**0.42**	148964	12.37	4354
Peak	**0.63**	222469	29.17	10301
Minimum	**0.10**	35313	2.67	943

Normalization	61	36

Annex 16d: Normalization data from comparing the concentration of the heavy metals in the biosolid to that found in the soil where they are applied.

	Cobre	**Cromo**	**Plomo**	**Zinc**
Average	180.3	103.9	83.7	1053.4
Maximum	449.39	2270	275.11	1887.0
Minimum	58.127	29.1	2.25	986.7
Conc. in Soil, mg/kg	110	11	43	228.0
Ratio	1.64	9.44	1.95	4.62
	4.09	206.36	6.40	8.28
	0.53	2.65	0.05	4.33
Normalization	69	97	70	93

Annex 16e: Normalization data for P and N recycled by the use of the biosolid generated.

	Total Nitrogen, TN		**Total Phosphorus, TP**	
	Concentration, mg/kg	**Load, kg/d**	**Concentration, mg/kg**	**Load, kg/d**
Average	29090	4314	12966	1923
Maximum	52692	7815	37739	5597
Minimum	3165	469	65	10
Normalization		48		66

Annex 16f: Normalization for comparing pollutant concentrations in the plant effluent to the receiving water bodies.

Parameters		**BOD5**		**TSS**	
		Effluent, g/m^3	**Load, Kg/d**	**Effluent, g/m^3**	**Load, Kg/d**
Total effluent load (kg/day)	**Average**	152	374587	87	214685
	Peak	225	555282	131	323262
	Minimum	94	232372	62	152994
Total load in rivers (kg/day)			529899		173769
Ratio	**Salitre-Av. WWTP**		1.41		0.81
	Salitre-Max. WWTP		0.95		0.54
	Salitre-Min.		2.28		1.14

	WWTP				
Normalization		65		55	

Annex 16g: Normalization for influent volume, community size and staff related data.

	Volume of Influent, m^3/d	Inh/m^3/d	m^2/m^3	Staff/m^3	Staff from community	Ratio
Average	353126	6.23	0.28	69	32	2.156
Maxiumn	378965	5.81	0.26	72	35	2.057
Minimum	264983	8.30	0.38	62	29	2.138
Normalization		83	83	30		23

Annex 16h: Normalization for cost related data.

	TC	OMC	EC	CC	UC	TC/UC
Average, \$/m^3/d	167.26	101.00	13.57	52.70	67.23	2.5
Minimum, \$/m^3/d	108.52	60.64	6.98	41.50	20.17	1.6
Maximum, \$/m^3/d	269.53	269.53	19.73	59.76	107.57	4.0
Normalization	64	81	48	39	46	64

Annex 16i: Normalization for biogas reutilization data.

	Average daily biogas production, m^3/day	Portion recycled for heat generation, m^3/day
Average	11955.8	3586.7
Maximum	18912.3	5673.7
Minimum	3180.2	954.1
Normalization	44	44

Annex 16j: Normalization for greenhouse related emissions from the WWTP.

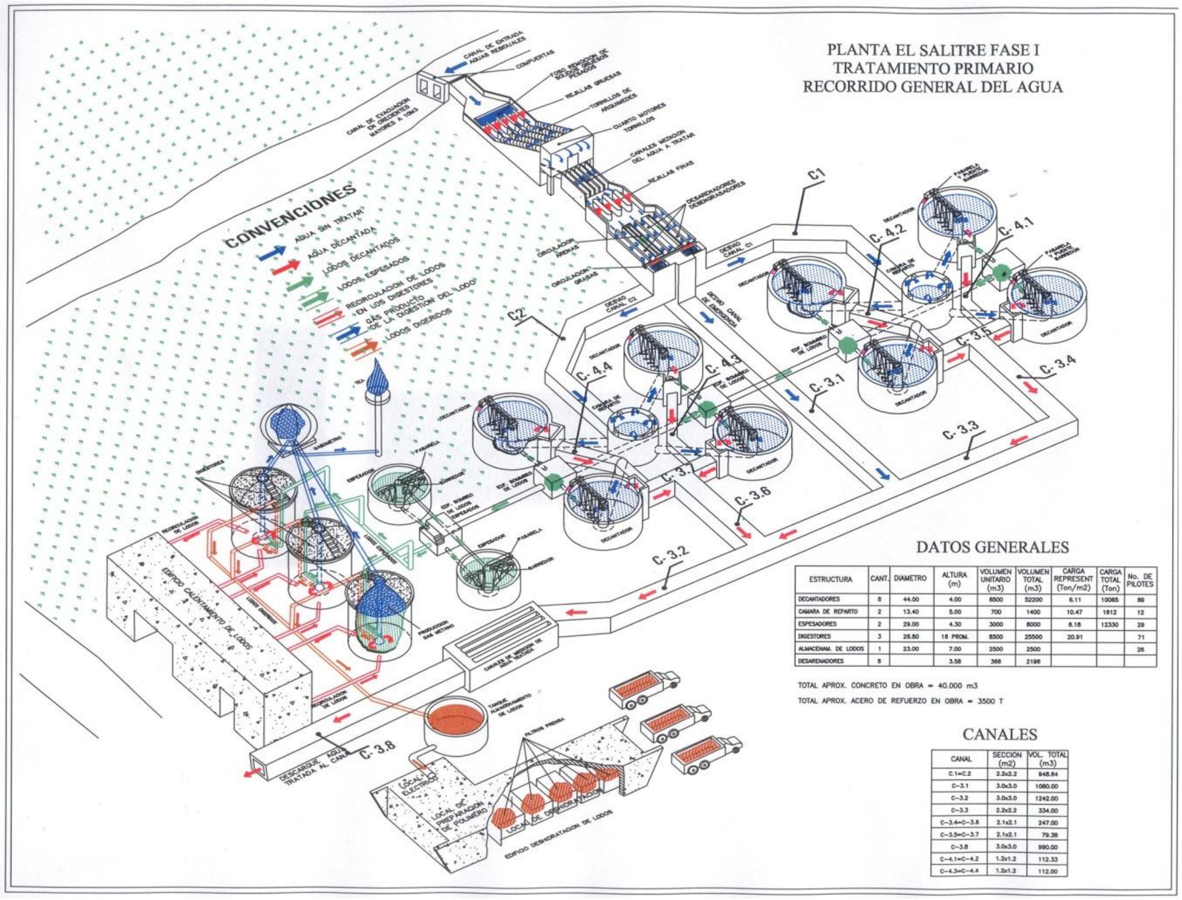
	Fuel Use	Operation/Process	Flaring	Total
Average	649	23589	15502	39740
Maximum	764	12200	28458	41422
Minimum	3329	31386	2914	37629
Normalization				44

Annex 17: Table summarizing the legal framework for Colombian water pollution control policy

Decree/Law	Regulation	Description
Decree-Law 2811 of 1974	National Natural Renewable Resources and Protection of the Environment Code	1. Charges the state with demarcating zones in which wastewater treatment is required and establishing concentration standards for various pollutants mandating that water users must obtain permits for discharging wastes from environmental authorities. 2. Mandates that any facilities or individuals using natural resources, including water, must pay fees for the damages associated with disposing of wastes.
Decree 1541 of 1978	Regulates the above code's provisions on water management	1. Stipulates that all discharges of solid, liquid, or gaseous wastes that could contaminate water or damage human health or the normal development of flora or fauna must be treated; the standards depend on the ecological and economic characteristics of the receiving body. 2. Lays the foundation for discharge fees authorizing INDERENA (National Institute of Natural Renewable Resources and Environment- *Instituto Nacional de los Recursos Naturales Renovables*) to charge the fees necessary to cover the costs of maintaining or replacing natural renewable resources. For wastewater dischargers, the fees are to take into account both the characteristics of the wastewater and the quality of the receiving water body within a duration limited to five years.
Decree 1594 of 1984		1. Establishes ambient water quality standards for different types of uses, including human and other domestic consumption; preservation of flora and fauna; agriculture, including irrigation; animal production; and recreation, including swimming. 2. Chapter VI of Decree 1594 governs discharges part of which forbids the discharge of liquid wastes into the streets or storm drains and aquifers, and the discharge of sediments, sludge, and solid substances from water treatment systems into water bodies or sewage systems. 3. The second part of Chapter VI establishes standards for wastewater discharges which depend on whether discharges go into water bodies, such rivers and lakes, or public sewers. 4. Chapters VII and VIII address wastewater discharge permit applications and requirements for monitoring of effluent standards within a five-year duration and the Ministry of Health (or other authority) endowed the right to inspect dischargers at any time and take samples of their effluents by provisions in Articles 162 and 163. 5. Requires the Ministry of Health (or other authority) to develop a resource classification plan for existing uses, projections of water use needs, quality simulation models, quality criteria, discharges procedures, and the preservation of the natural characteristics of the resource. The quality simulation models should contain, at a minimum, BOD, QOD, TSS, pH, temperature, dissolved oxygen, carried water, hydrobiologic information, and total coliforms. 6. States that the Ministry of Health (or other authority) can request an environmental impact assessment for (i) discharges that contain substances of sanitary interest; (ii) energy generation projects; (iii) exploration and extraction of nonrenewable resources; (iv) modifications of the course of waters between basins; (v) construction of aerial, maritime, and fluvial terminals; (vi) civil works that involve earthmoving; (vii) exploration of riverbeds, marine beds, and substrata; and (viii) new human settlements and industrial parks. 7. Give the Ministry of Health (or other authority) the authority to apply any of the following sanctions: (i) temporary shutdown; (ii) permanent suspension of works; (iii) confiscation of objects; (iv) destruction or denaturalization of articles; and (v) temporary suspension of sales or employment of products while a decision is being made.
Law 99 of 1993	Created National Environmental System (*Sistema Nacional Ambiental,* SINA)	1. Created the Ministry of Environment (MMA) and assigned it several responsibilities relevant to water management, including the general obligation to conserve and manage the environment and natural resources, and the more specific obligation to promulgate water quality and wastewater discharge standards. 2. Extended and redefined the purview of the autonomous regional corporations (CARs) giving them the principal responsibility of monitoring and enforcing water quality regulations, including the discharge standards and fees. It also established urban environmental authorities (AAUs) in cities with populations greater than 1 million inhabitants and charged them with responsibilities analogous to those of CARs.

		3. Mandates that any activity that could cause serious environmental damage or significantly modify the landscape requires an environmental license. 4. Mandates penalties (*tasas retributivas*) for the disposal of wastes into water (among other natural resources).
Decree 901 of 1997	Regulate discharge fees for water discharges.	1. Pollutants covered are to be identified by the Ministry of Environment (which subsequently named BOD and TSS). 2. Establishes the monthly fee charged to water users depending on these two factors: (i) the amount of BOD and TSS in the facility's effluent stream, and (ii) whether the total discharges from all sources in a defined water basin meet targets set for each basin. 3. Article 5 concerns target setting where every five years the board of directors of the competent environmental authority—CAR or AAU—is to establish a six-month reduction goals for total discharges of BOD and TSS into a water basin or segment
Decree 3100 of 2003,		1. Article 6 of the Decree establishes that, prior to collecting the penalty, the environmental authority—usually the CAR or AAU—should (i) evaluate the quality of the water sources; (ii) identify the dischargers that are required to pay penalties; (iii) ensure that those dischargers have discharge plans or licenses; and (iv) establish the quality objective for the receiving water body. 2. Article 11 establishes that the users of the same water source can agree to modify the individual or collective level of discharge reduction as long as increases from one discharger are offset by reductions from other dischargers.

Annex 18: Schematic diagram of the El Salitre WWTP.



DATOS GENERALES

ESTRUCTURA	CANT.	DIAMETRO	ALTURA (m)	VOLUMEN UNITARIO (m3)	VOLUMEN TOTAL (m3)	CARGA REPRESENT (Ton/m2)	CARGA TOTAL (Ton)	No. DE PILOTES
DECANTADORES	8	44.00	4.00	6500	52200	6.11	10065	69
CAMARA DE REPARTO	2	13.40	5.00	700	1400	10.47	1612	12
ESPESADORES	2	29.00	4.30	3000	6000	6.18	12330	29
DIGESTORES	3	26.80	16 PROM.	8500	25500	20.91		71
ALMACENAM. DE LODOS	1	23.00	7.00	2500	2500			26
DESARENADORES	6		3.58	366	2196			

TOTAL APROX. CONCRETO EN OBRA = 40.000 m3

TOTAL APROX. ACERO DE REFUERZO EN OBRA = 3500 T

CANALES

CANAL	SECCION (m2)	VOL. TOTAL (m3)
C.1=C.2	2.2x2.2	948.64
C-3.1	3.0x3.0	1080.00
C-3.2	3.0x3.0	1242.00
C-3.3	2.2x2.2	334.00
C-3.4=C-3.6	2.1x2.1	247.00
C-3.5=C-3.7	2.1x2.1	79.36
C-3.8	3.0x3.0	990.00
C-4.1=C-4.2	1.2x1.2	112.33
C-4.3=C-4.4	1.2x1.2	112.00