CHALMERS
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The assessment of small wastewater treatment plants in Cochabamba, Bolivia

A framework for using sustainable development indicators

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

Magdalena Huber

Department of Civil and Environmental Engineering
Division of Water Environment Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Examensarbete ACEX60-18-5/ Institutionen för bygg- och miljöteknik,
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Cover:
Maturation pond in a newly installed plant in the Valle Alto, County of Cochabamba, Bolivia. *Author's own copyright*.

Department of Civil and Environmental Engineering, Göteborg, Sweden, 2018

Abstract

At the present, it is estimated that 92 % of the wastewater in developing countries is treated insufficiently and hence, harmful constituents released to the environment pose a risk on ecosystems and human health. This situation is unacceptable, and solutions must be found to implement new and enhance existing wastewater treatment systems. The aim of this study is the assessment of the sustainability performance of two small wastewater treatment plants (WWTPs <2000 p.e.) in Cochabamba, Bolivia. To address all aspects of sustainability, a set sustainable development indicators (SDIs) was generated. The selection of relevant SDIs in accordance to the conditions at the specific WWTPs is a crucial step to avoid the obtainment of unrelated information. The acquisition of data corresponding to the SDIs occurred through the execution of surveys and the analysis of the wastewater characteristics. This step was the most challenging part and some relevant information could not be collected. Moreover, major limitations were the quantity of qualitative data and, as common for studies in Latin America, the difficulties to find benchmarks to compare to. At both WWTPs, there was great ambition of making their systems sustainable; however, the means and the expertise to achieve sustainability were missing. The most important finding was the lack of adequate O&M due to the unavailability of instructions and mal-design of the treatment units. The consequence is the failure of the WWTP in terms of meeting the removal efficiency of wastewater constituents, and hence, the discharge of those to the recipient water. As suggested by many researchers, a change is needed regarding project planning and policy implementations. Those changes can be addressed by the introduction of guidelines that have the potential to facilitate the planning phase and provide a structured approach to problems. The set of SDIs could be used within a guideline to assess the sustainability of existing plants, but moreover, could be applied in the planning phase of new WWTPs and ensure the success of development projects. The sustainability indicators identified to be most significant were: *available technical human resources, operational cost, amount of wastewater treated and received, complexity of O&M, maintenance cost.*

Key words: Developing countries, Small wastewater treatment plants, Sustainability, Sustainable development indicators, Urbanisation.

Resumen

En la actualidad, se estima que el 92% de las aguas residuales en los países en desarrollo se tratan de manera insuficiente y, por lo tanto, los componentes nocivos emitidos al medio ambiente representan un riesgo para los ecosistemas y la salud humana. Esta situación conlleva serios problemas a muchos niveles, por lo que es urgente la solución e implementación de nuevos y mejores sistemas de tratamiento de aguas residuales. El objetivo de este estudio es evaluar el desempeño de sostenibilidad de dos pequeñas plantas de tratamiento de aguas residuales (PTAR <2000 p.e.) en Cochabamba, Bolivia. Para abordar todos los aspectos de la sostenibilidad, se generó un conjunto de indicadores de desarrollo sostenible (ingles: sustainable development indicators - SDIs). La selección de las SDI relevantes que están de acuerdo con las condiciones de las PTAR específicas es un paso crucial para evitar la obtención de información no relacionada. Las adquisiciones de datos correspondientes a los SDIs se obtuvieron a través de la realización de encuestas y el análisis de las características de las aguas residuales. Este paso fue la parte más difícil y no se pudo recopilar alguna información relevante. Además, las principales limitaciones fueron la cantidad de datos cualitativos y, como es común en estudios previos en América Latina, las dificultades para encontrar puntos de referencia para comparar. En ambas PTAR, había una gran ambición de hacer que sus sistemas fueran sostenibles; sin embargo, faltaban los medios y la experiencia para lograr la sostenibilidad. El hallazgo más importante fue la falta de O&M adecuada debido a la falta de disponibilidad de instrucciones y al mal diseño de las unidades de tratamiento. La consecuencia es el fallo de la PTAR en términos de cumplir con la eficiencia de eliminación de los constituyentes de las aguas residuales y, por lo tanto, la descarga de estos al agua del receptor. Según lo sugerido por muchos investigadores, se necesita un cambio con respecto a la planificación de proyectos y la implementación de políticas. Estos cambios se pueden abordar mediante la introducción de directrices que tienen el potencial de facilitar la fase de planificación y proporcionar un enfoque estructurado de los problemas. El conjunto de SDIs podría usarse dentro de una guía para evaluar la sostenibilidad de las plantas existentes, además, de poder aplicarse en la fase de planificación de nuevas PTAR y garantizar el éxito de los proyectos de desarrollo. Los indicadores de sostenibilidad identificados como más significativos fueron: recursos humanos técnicos disponibles, costo operacional, cantidad de aguas residuales tratadas y recibidas, complejidad de O&M, costo de mantenimiento. Palabras clave: países en desarrollo, pequeñas plantas de tratamiento de aguas residuales, sostenibilidad, indicadores de desarrollo sostenible, urbanización.

Palabras clave: países en desarrollo, pequeñas plantas de tratamiento de aguas residuales, sostenibilidad, indicadores de desarrollo sostenible, urbanización.

Abstrakt

För närvarande är det uppskattat att 92% av avloppsvattnet i utvecklingsländerna behandlas otillräckligt och att skadliga beståndsdelar som släpps ut i miljön utgör en risk för ekosystem och människors hälsa. Denna situation är oacceptabel, och lösningar måste hittas för att genomföra nya och förbättra befintliga avloppsreningssystem. Syftet med denna studie är att utvärdera hållbarhetsprestandan för två små avloppsreningsverk (WWTPs <2000 p.e.) i Cochabamba, Bolivia. För att ta itu med alla aspekter av hållbarhet genererades en uppsättning indikatorer för hållbar utveckling (SDI). Urvalet av relevanta SDI i enlighet med villkoren vid de specifika växtskyddsområdena är ett viktigt steg för att undvika uppkomsten av orelaterad information. Förvärvet av data som motsvarar SDI:erna uppstod genom genomförandet av undersökningar och analysen av avloppsegenskaperna. Detta steg var den mest utmanande delen och vissa relevanta uppgifter kunde inte samlas in. Dessutom var en stor begränsning mängden av kvalitativa data och, som vanligt för studier i Latinamerika, svårigheterna att hitta jämförelseindex med. Vid båda WWTP:erna var det en stor ambition att göra sina system hållbara; emellertid saknades medel och kompetens för att uppnå hållbarhet. Det viktigaste konstaterandet var bristen på adekvat O & M på grund av otillgängligheten av instruktioner och dålig design av behandlingsenheterna. Konsekvensen är att WWTP har misslyckats när det gäller att uppfylla avlägsnandeeffektiviteten hos avloppsvattenbeståndsdelar, och därmed utsläpp av dessa till mottagarens vatten. Som tidigare föreslagits av många forskare behövs en förändring när det gäller projektplanering och genomförande av politiken. Den förstnämnda kan hanteras genom införande av riktlinjer som har potential att underlätta planeringsfasen och ge ett strukturerat förhållningssätt till problemen. Uppsättningen av SDI kan användas inom specifika riktlinjer för att bedöma hållbarheten hos befintliga anläggningar, men kan också användas i planeringsfasen av nya WWTP och säkerställa framgången vid utvecklingsprojekt. De hållbarhetsindikatorer som identifierades som mest betydande var: tillgängliga tekniska personalresurser, driftskostnader, mängd behandlat och mottaget avloppsvatten, komplexitet på O & M, och underhållskostnader.

Nyckelord: Utvecklingsländer, Små avloppsreningsverk, Hållbarhet, Indikatorer för hållbar utveckling, Urbanisering.

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1 Introduction

All terrestrial life on earth is dependent on freshwater (Skinner and Murck, 2011). The human species relies on plants, and plants again need water to subsist. Looking at the planet earth, it appears to be covered by water, but in fact, only 2.5 % of the total amount of water is fresh water (see Figure 1), of which around 74 % is stored in glaciers or permanent snow cover, and accordingly, 26 % is accessible in the form groundwater (98.5 %) and surface water (1.5 %).

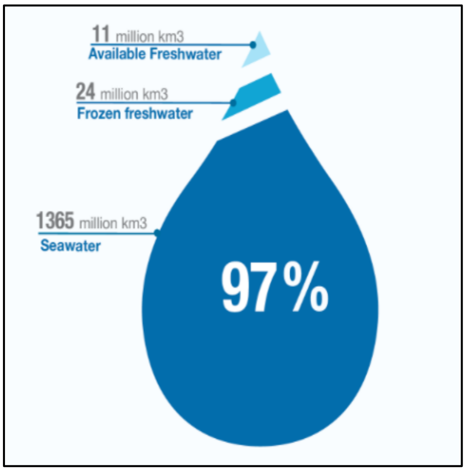


Figure 1: The World´s Water Resources. *Source: Veale (2015).*

Many countries currently face water scarcity, physical or economic (Symonds et al., 2014), as freshwater is no longer considered an unlimited resource (Arnell, 2004). Already before the year 2000, researchers estimated that many countries were overexploiting their available freshwater resources by 20 %. One cause of the overconsumption is the amount of water used for irrigation (see Figure 2), which accounts for 70 % of the total amount of freshwater extracted globally (Sustainable Development Solutions Network, 2016). This may, in fact, cause a risk to society and the environment as it is threatening the availability of freshwater for ecosystems as well as for drinking water and food production purposes (Ridoutt and Pfister, 2010).

In addition to overconsumption, a primary concern is the discharge of untreated sewage is a threat to water resources. The sewage of approximately 20 % of the population (Verbyla et al., 2016) and an estimated 80 % of all wastewater produced by human activities is discharged to recipient water without being treated (Sustainable Development Solutions Network, 2016). The consequences on ecosystem services, especially the decrease of the quality of surface waters puts public health at risk, subsequently affecting economic prosperity (Andersson et al., 2016). Previous studies have reported that the consumption of water contaminated with faecal coliforms can result in diarrhoea which can lead to death (Quick et al., 1999).

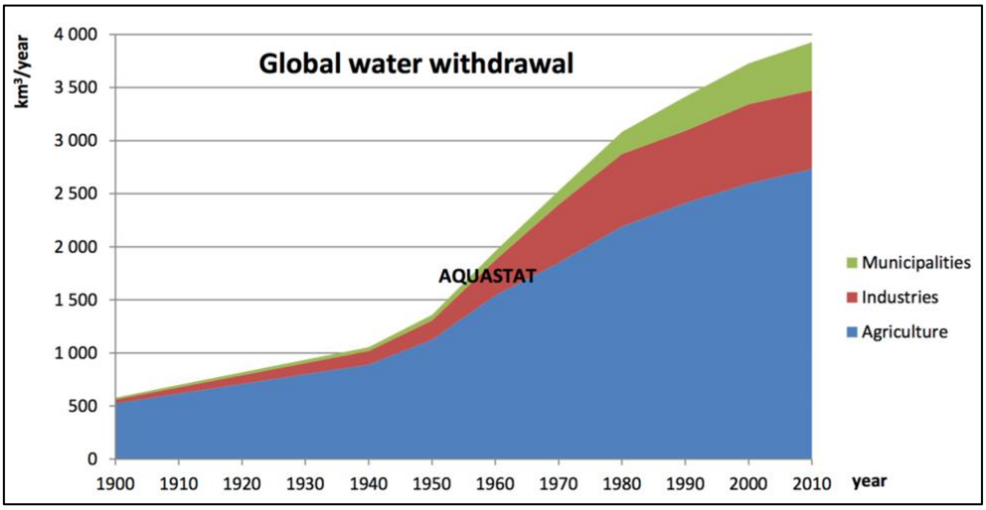


Figure 2: Global water withdrawal from 1900 to 2010. *Source: Water uses (2010).*

The population growth in developing countries comes along with an increase of the global demand on water in form of potable water usage and irrigation (Verbyla et al., 2013), and is expected to have increased by 55 % in 2050 (WWAP, 2015). The consequence is higher wastewater flows (Parkinson and Teyler, 2003). In 2000, 86 % of the wastewater produced in Latin America was released untreated to the environment (Martijn and Redwood, 2005). According to Verbyla et al. (2013), there is a strong migration towards urban areas in developing countries and 50 % of the population lives in cities with <500 000 inhabitants, which are expected to grow with a factor of 1.5 until 2025. The life of people in these areas is strongly reliant on healthy ecosystems. Assuming an increased volume of wastewater effluent, these rapid changes are having a serious effect and severe consequences are to be expected. In this regard, wastewater systems must be designed, adopted and planned to cope with increased wastewater flows resulting out of a fast urbanization process.

Even in high-income countries, wastewater is released untreated to recipient water (Andersson, 2016) or not sufficiently treated as e.g. in the rural areas of Sweden, where small-scale wastewater systems do often not comply with the standards set in the Swedish Environmental Code (Swedish Environmental Protection Agency, 2016). The difference to developing countries is, however, significant: up to 92 % of the wastewater enters nature without being treated adequately beforehand (Andersson, 2016). In Figure 3, this difference is visualized by showing that the required effluent quality is barely met in developing countries (Von Sperling and de Lemos Chernicharo, 2002). The reuse of wastewater for irrigation is an increasingly important area in developing countries; despite, often the wastewater was not or not sufficiently treated, threatening health and environment (Symonds et al., 2014).

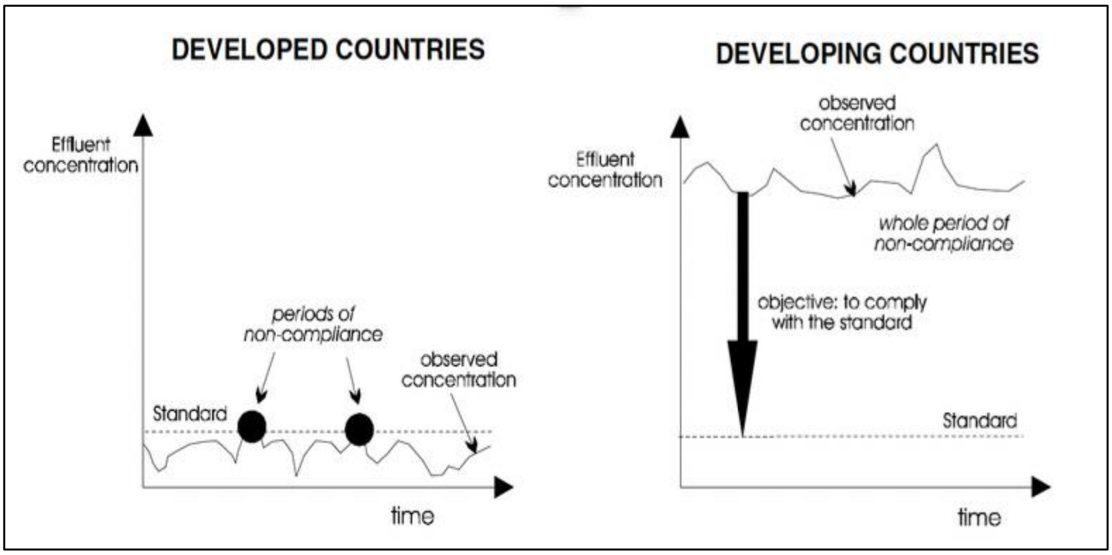


Figure 3: The difference in compiling with the discharge standards in developed (left) and developing (right) countries. *Source: Von Sperling and de Lemos Chernicharo (2002).*

Because safe drinking water, improved sanitation and sufficient wastewater treatment are essential for sustainable development (Palme et al., 2005), the sustainable management of urban water systems in developing countries is highly important to prevent nature and humans from further harm, and hence, is a key aspect of creating a sustainable development in the future (Verbyla, 2013).

One challenge is, therefore, to make sustainable choices within the sector of wastewater treatment systems (Singhirunnusorn and Stenstrom, 2009). It was revealed that 40 % of projects related to water are malfunctioning (Fogelberg, 2013), and the lack of management and safe handling of the wastewater, often due to failure within the operation and maintenance (O&M) as well as due to lack of support by the government, was identified a major concern in developing countries (Andersson et al., 2016). Bakir (2001) suggests that successful wastewater management services are dependent on basing the solutions on environmental, social, cultural and economic circumstances. The choices must address the site-specific conditions and should be not taken because it worked somewhere else.

Sustainable development indicators (SDIs) were introduced as a tool to holistically evaluate and to select appropriate systems that meet the concept of sustainability in terms of social, environmental, economic and technical aspects (Singhirunnusorn and Stenstrom, 2009). With these indicators, the aim is to capture the sustainability of the system as accurate as possible, considering the variables within the dimensions of sustainability.

1.1 Problem description

The development of peri-urban areas of cities in low-income countries takes places without being planned and is often not officially regulated (Parkinson, 2003). A major problem with this unplanned development is a lack of infrastructure and subsequently, no access to a safe water supply and improved sanitation services. This further leads to negative impacts on the environment in the form of polluted surface and groundwater, as well as negative impacts on human health through the occurrence of harmful pollutants and pathogens in the water supply. The efforts to change the situation are often community driven.

One aspect that requires attention is the use of insufficiently-treated wastewater for irrigation in peri-urban areas. While high levels of nutrients and inexistent supply costs make the use of wastewater interesting for farmers, the production and consumption of vegetables irrigated with wastewater can have an impact on the health of both producer and consumer.

Rapidly growing and often informal peri-urban settlements are rarely connected to the centralized municipal sewer network. In recent year, more attention has therefore been paid to smaller decentralized wastewater treatment systems (Massoud et al., 2009). Policies need to be developed to support the planning and implementation of those and imply a higher responsibility for local institutions. The systems must be designed carefully and implemented properly to ensure its operation and hence, its long-term functionality. As decentralized systems are often managed by the local community, there is a need to ensure they are properly managed. In that perspective, there must be a clear organization of responsibilities within the system as for management, operation and maintenance. The availability of qualified people must be considered when choosing treatment technologies (Parkinson, 2003). For this, educational training programs are recommended to teach both future employees and also the residents (Massoud et al., 2009).

This study investigates two WWTPs in peri-urban areas in Cochabamba. The systems treat the wastewater of < 2000 p.e. collected through a small sewer network and are considered to be semi-centralised systems (Libralato et al., 2012). A number of previous studies reported that those systems have a lower impact on the environment and offer a facilitated reuse of the treated wastewater.

Due to the growing importance of decentralised and semi-decentralised systems in developing countries, it is fundamental to ensure their sustainability and therefore, identify key dimensions and indicators to monitor sustainability. This can be done by assessing existing treatment systems. In this work, the assessment was used to find solutions for the enhancement of the implementation of semi-decentralised WWTPs in developing countries.

1.2 Aim and purpose

The main objective of this work is to create a framework for assessing small wastewater treatment plants (WWTP <2000 p.e.) in developing countries. The framework is based on a set of sustainable development indicators (SDIs) and will be applicable to different locations by selecting indicators according to their situational relevance. For this purpose, two WWTPs in the peri-urban area of Cochabamba, Bolivia, will be investigated by applying both quantitative and qualitative methods. This case study seeks to identify their strengths and weaknesses by comparing the obtained results to guideline values and findings from previous studies. The outcome will advance the understanding of issues occurring within the wastewater sector in developing countries.

A secondary objective is to establish the potential practical application of a set of SDIs, apart from its use for the assessment of the sustainability and the comparison between systems' performances. A special focus is set on its implementation in the planning phase of WWTPs in developing countries to ensure their sustainability performance and the findings should make an important contribution to the field of development work. Accordingly, the indicators that are found to be significant, will be emphasised in the framework. The focus on the planning phase will result in economic benefits, environmental protection and a better environment and health situation in the region due to sustainable functioning wastewater treatment plants.

1.3 Limitations

During the obtainment of the results and their interpretation, limitations of this study were encountered. A major source of uncertainty can be found within the methodology and its realisation. Moreover, the scope of this investigation is limited when considering the formulated aim.

The listed limitations must be considered when following this report:

- Simplified methods were applied to achieve the aim of this research,
- a lack of expertise and a barrier due to the language influenced the formulation and interpretation of the conducted surveys,
- the sample size for the surveys was sufficient for a first impression of the situation but was too small to be representative.

1.4 Thesis organisation

This thesis has been divided into eight chapters, including this introductory chapter. The next Chapter Two covers the background information needed to follow the remaining chapters and presents the issues related to drinking water and wastewater services, as well as an introduction to sustainability. The methodology that was followed during this work is explained in the third Chapter. In Chapter Four, the case study is described by first explicating why the two wastewater treatment plants were chosen, and then by presenting the configurations of the two investigated wastewater treatment plants. The results obtained by following this methodology are presented in Chapter Five. The next step was to discuss the findings, and this was done within Chapter Six in which, additionally, the limitations of this study are mentioned briefly. In Chapter Seven, the potential future practical applications of the SDIs are presented, and recommendations derived from previous studies are given. The final Chapter Eight consists of a brief summary and critique of the findings and provides both recommendations on what can be improved at the investigated WWTPs and an outlook on further research.

2 Theory

The Chapter Two provides background information about the country, its cities and its population, and also about the poverty situation and the process of urbanization within it (Section 2.1). Moreover, the provision of drinking water and sanitation services are presented in Section 2.2 on a global level, for Bolivia and for the case of Cochabamba, respectively. The remaining part of this chapter is concerned with a more detailed background about the processes and the situation related to water in Cochabamba (Section 2.3) and an introduction on wastewater treatment systems (Section 2.4) and their sustainability (Section 2.5).

2.1 The Bolivian context

Bolivia is a country in central South America with borders to Peru, Brazil, Paraguay, Argentina and Chile (Borsdorf and Stadel, 2015). Paraguay and Bolivia are the only landlocked countries in South America, i.e. they lack access to both the Pacific and the Atlantic Ocean (CIA, 2017). In total, there exist nine departments in Bolivia (see Figure 4) (Nickson, 2002).

Figure 4: Map of Bolivia with the nine departments differently coloured. *Source: Map retrieved on 21/08/2018 from https://geology.com/world/bolivia-satellite image.shtml*

Bolivia, as a developing country with semi-arid climate conditions, faces challenges in terms of sustainable development within the water sector. The climate condition within the country vary due to a high geographical diversity; from the Andeans highlands and salt deserts to tropical regions. The Ministerio de Medio Ambiente y Agua (2013) asserts that changes in the climate are the reasons why some parts of the country face water scarcity. However, Larsen et al. (2018) argue that the water scarcity is often mainly economic, meaning that there is a lack of investment into water supply services to use the available water resources (Brown and Matlock, 2011).

More than two-thirds of the population are indigenous with the two main groups Aymara and Quechua (Carmen Ledo, 2002). The official language is Spanish, spoken by 60.7 % of the population, but all indigenous languages are acknowledged as official, of which Quechua and Aymara are spoken by 21.2 % and 14.6 % of the population.

2.1.1 Bolivian cities and their population

The population of the Plurinational State of Bolivia has increased by more than 3 million within the last two decades and currently accounts to 11 051 600 inhabitants; by 2025, this number is estimated to reach more than 12.3 million (UN, 2017). It was recorded that 69.3 % of the country's population is living in urban areas (CIA, 2017); and the cities continue to grow (UN, 2016). The main cities are Sucre, La Paz, El Alto, Santa Cruz and Cochabamba.

The city of Sucre, with only 300 000 inhabitants, is the capital of the country (Borsdorf and Stadel, 2015), while La Paz, on an average elevation of 3 650 m a.s.l., is the seat of the government, with over 835 400 inhabitants (data from 2010) and its urban agglomeration, counting in the cities of El Alto and Viacha (Borsdorf and Stadel, 2015), accounts to 1 834 000 (UN, 2016). However, Santa Cruz de la Sierra with 1 616 100 inhabitants (data from 2010) and El Alto located on 4 100 m a.s.l. with around 953 000 inhabitants (data from 2010) are the two highest populated cities in Bolivia (Borsdorf and Stadel, 2015). In the city of Cochabamba live approximately 630 000 people and the number of inhabitants for the entire metropolitan area accounts for more than 1 273 000 (UN, 2016).

2.1.2 Poverty and urbanization in Bolivia

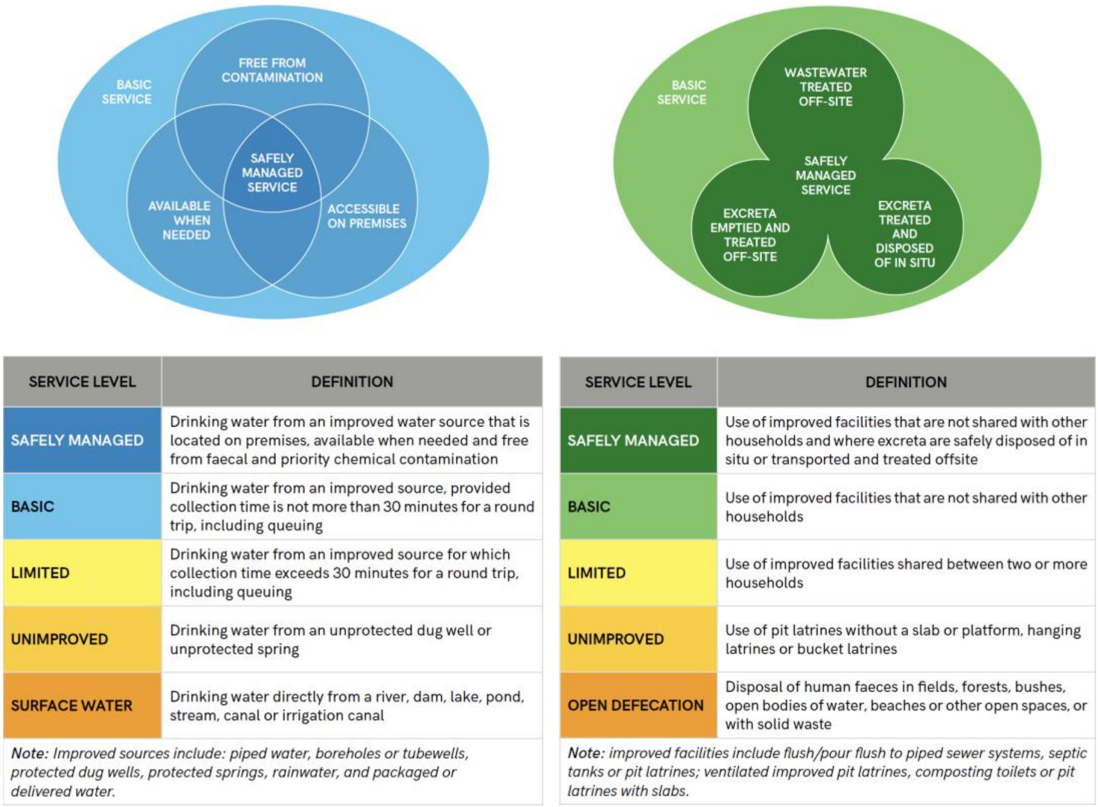
The Human Development Index (HDI) was found to be 0.6 for Bolivia (Carmen Ledo, 2002). The Gross Domestic Product (GDP) accounts for 33,94 billion US-dollar. The life expectancy was 69,13 years in 2016 at birth compared to 60,69 in 1999 (data from the World Bank). In 2012, infant mortality was estimated to 32,8 % (GLAAS, 2015).

In 1992, it was estimated that 70 % of the population is classified as poor, of which 94 % lived in rural areas (Grootaert and Narayan, 2004). A majority of the people being classified as poor also are indigenous and only 10 % of them live in urban areas (Carmen Ledo, 2002). Poverty is a push-factor for people to leave the countryside, while the economic prosperity is a pull-factor towards the cities (Jedwab et al., 2017). This is speculated to be a reason why the population living in urban areas increased from 50 % in 1992 to 65 % in 1996 (Grootaert and Narayan, 2004) and to 69 % in 2015 (WHO, 2017). Carmen Ledo (2002) found that strong urbanization can be associated with the country being in a period of change.

2.2 Services for drinking water and sanitation

The data in the following sections were obtained in the year 2015 and were published in 2017 by the World Health Organisation (WHO) and the United Nations Children's Fund (UNICEF) in the report "Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines" or were retrieved online from the World Bank Group.

According to the WHO (2017), safely managed drinking water service is defined by "drinking water from an improved water source that is located on premises, available when needed and free from faecal and priority chemical contamination; and safely managed sanitation service is the "use of improved facilities that are not shared with other households and where excreta are safely disposed of situ or transported and treated offsite. The definition of the service levels of drinking water sources and sanitation services is given in Figure 5.



SERVICE LEVEL	DEFINITION
SAFELY MANAGED	Drinking water from an improved water source that is located on premises, available when needed and free from faecal and priority chemical contamination
BASIC	Drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip, including queuing
LIMITED	Drinking water from an improved source for which collection time exceeds 30 minutes for a round trip, including queuing
UNIMPROVED	Drinking water from an unprotected dug well or unprotected spring
SURFACE WATER	Drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal

Note: *Improved sources include: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.*

SERVICE LEVEL	DEFINITION
SAFELY MANAGED	Use of improved facilities that are not shared with other households and where excreta are safely disposed of in situ or transported and treated offsite
BASIC	Use of improved facilities that are not shared with other households
LIMITED	Use of improved facilities shared between two or more households
UNIMPROVED	Use of pit latrines without a slab or platform, hanging latrines or bucket latrines
OPEN DEFECATION	Disposal of human faeces in fields, forests, bushes, open bodies of water, beaches or other open spaces, or with solid waste

Note: *improved facilities include flush/pour flush to piped sewer systems, septic tanks or pit latrines; ventilated improved pit latrines, composting toilets or pit latrines with slabs.*

Figure 5: Categorisation drinking water sources (left) and sanitation services (right) according to the WHO, 2017. *Source: Report "Progress on drinking water, sanitation and hygiene" by WHO and UNICEF (2017).*

The world's population accounts to 7,44 billion people (data from 2016, World Bank, 2017). 71 % of the global population, 10 % more compared to 2000, receive safely managed drinking water service, and 2 %, which are 2 % less than in 2000, use surface water as drinking water source (data from 2015, WHO, 2017). In Latin America, 90 % of the population uses at least basic drinking water services and 65 % using safely managed improved water supplies. As shown in Figure 6, only in Peru less than 90 %

receive basic drinking water service. It can also be seen that Africa is the continent with the lowest coverage of basic drinking water service.

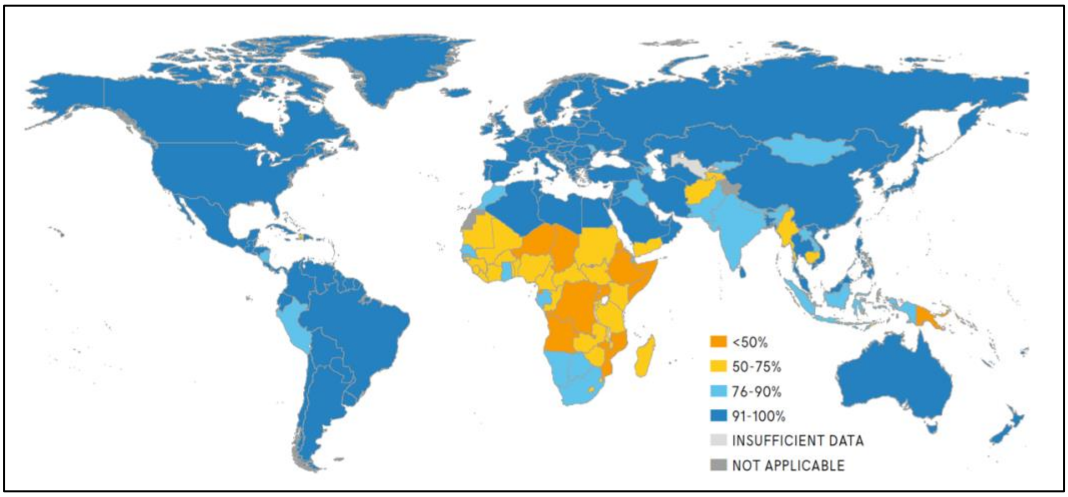


Figure 6: World map showing the coverage of countries with at least basic drinking water services. *Source: Report "Progress on drinking water, sanitation and hygiene" by WHO and UNICEF, 2017.*

Safely managed sanitation services are provided for only 39 % of the global population, which is 10 % more than in 2000, 90 % of them living in urban areas, and 12 % still practice open defecation, which is 8 % less than in 2000 (data from 2015, WHO, 2017). In the last 15 years, the number of people using open defecation decreased with an annual rate of change of -0,53; however, to reach 0 by 2030, the process must be fastened up. From Figure 7 it can be retrieved that in South America, basic sanitation services are provided for more than 91 % of the population in Chile, Argentina and Venezuela, Uruguay and Guiana.

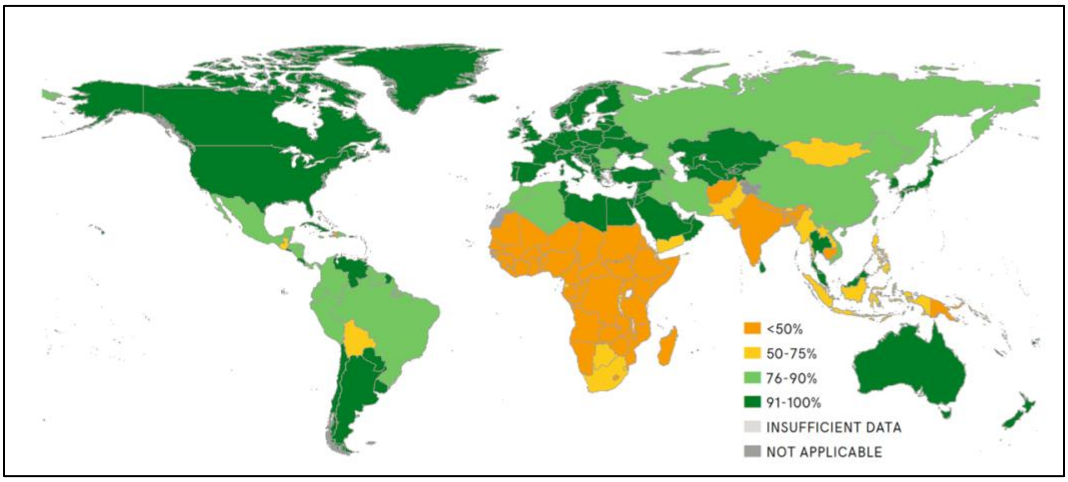


Figure 7: World map showing the coverage of countries with at least basic sanitation services. *Source: Report "Progress on drinking water, sanitation and hygiene" by WHO and UNICEF (2017).*

2.2.1 Access to drinking water and sanitation services in Bolivia

The president of the country, Evo Morales, supported the idea of considering the "access to drinking water and sanitation as a fundamental human right" (GLAAS, 2015). The Ministry of Environment and Water (MMAyA) is the organisation for water and sanitation supply within the country. In 2011 the "My water project" which is a program to achieve Millennium Development Goals by "More Investment for Drinking-Water" was initiated and 2 years later, 81 % of the country's water consumption was coming from improved drinking water sources, where the water quality is analysed regularly (see Figure 8), accompanied by the connection of 260 000 rural families to the drinking water system. Contrary to that progress, there was no such improvement in the access to sanitation.

Figure 8: Student of the University of San Simón regularly takes samples at drinking water plants in the department of Cochabamba. *Author's own copyright (Photo was taken in March 2018).*

In 2015, 93 % of the country's population had access to at least basic drinking water services (data from 2015, WHO, 2017). An average of 83 % of the population in Bolivia is connected to the drinking water system (Baer, 2015). The difference between rural and urban accounts to 20 % more in urban areas (data from 2015, WHO, 2017). However, the annual rate of change from 2000 to 2015 in rural areas was 1,75 while in the urban areas it was 0,29. There are no data available for the proportion of the population using improved water supplies.

The access to safe sanitation was described by Andersson et al. (2016) as an indicator "of inequality and disadvantage" and within Bolivia, it was found that only approximately 20 % (data from 2015) of the population had access to improved sanitation (WHO, 2017). Furthermore, it is the only country in South America that provides basic sanitation services to less than 75 % of its population (see Figure 7) (data from 2015, WHO, 2017). Contrary to the high coverage with basic drinking water services, basic sanitation is provided for only 53 % and open defecation is practised by 14 % of the population, where 40 % of the rural population and only 3 % of the urban population are affected. The annual rate of change in basic sanitation services is 0,96 national wide: 0,91 in urban and only 0,6 in rural areas. The annual rate of change in open defecation, that is the reduction of this practice, is -1,48 in rural and -0,85 in urban areas. There is no data available for safely managed sanitation services in rural areas, but 22 % of the population in urban areas are using improved sanitation facilities that are safely managed (data from 2015, WHO, 2017).

2.3 The case of Cochabamba

The city, founded in the 18th century (Carmen Ledo, 2002), is located in a valley on an average altitude of 2 500 m above sea level (Montes and Camacho, 2007). In Figure 9, a picture of the city taken during the rain period gives an impression of the valley the city is located in. The semi-arid climate is characterised by an average yearly temperature of 17.5 °C that merely changes during the year and an annual precipitation rate of 450 to 550 mm (Zabalaga et al., 2007). The total precipitation takes place during the months of October to April (Neuman-Redlin et al., 2000).

Figure 9: Cochabamba city. The picture was taken from "Cerro San Pedro*". Author's own copyright (Photo was taken in February 2018).*

2.3.1 Urbanization in Cochabamba

The department of Cochabamba has borders with six other departments, making it the most central one (Carmen Ledo, 2002). It is, therefore, the region to be crossed to get from east to west, which is the most important route, connecting Santa Cruz in the east with La Paz in the west. The road to Santa Cruz goes through the Sacaba while the road to Lap Paz passes Quillacollo. These two cities are located in 15 km distance from the city of Cochabamba, but these cities connected through the urbanization of the metropolitan area, as can be seen in Figure 10.

The valley of the city makes up 5 % of the department and is characterized by its agricultural prosperity (see Figure 11), but the continuing growth of the peri-urban areas endangers the agriculture practised in the valley (Carmen Ledo, 2002). Already more than 15 years ago, 18 000 ha of the total valley area of 39 0000 ha were covered by urban structures.

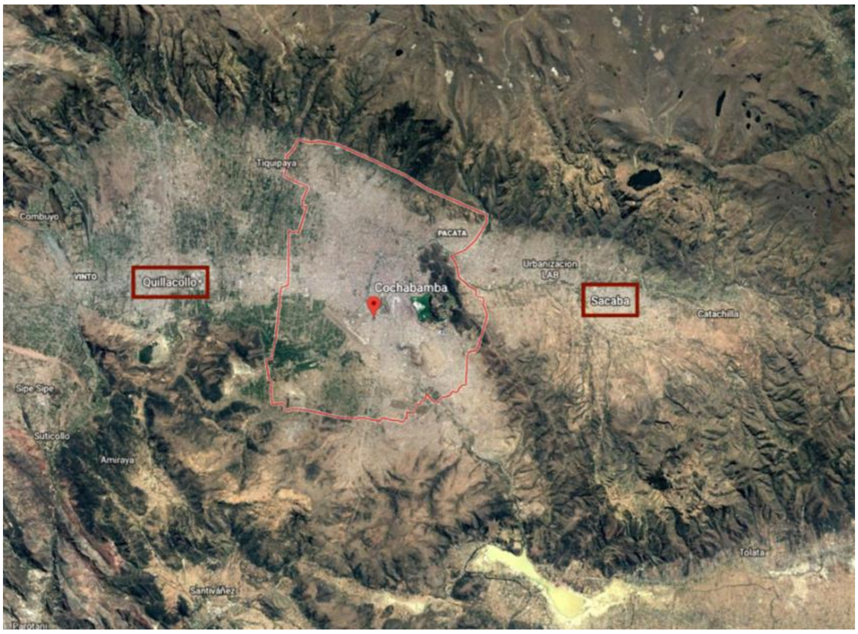


Figure 10: Map of the city of Cochabamba (framed in red) and its metropolitan area with the cities of Quillacollo (in the west) and Sacaba (in the east). *Source: Retrieved from Google Earth on 5/07/2018.*

Figure 11: Farmers working on a field. The picture was taken in the province Quillacollo in the west of Cochabamba city. *Author's own copyright (Photo was taken in March 2018).*

The environmental impact due to the population growth was observed in form of different types of pollution: air pollution due to increasing emissions, soil and water pollution due to lack of sanitation service and garbage handling. To cope with the accelerating urbanisation, the concept of municipal districts was introduced. In total, there exist now thirteen districts and each is supposed to manage its health, education and infrastructure. Hence, the decentralisation yields to a more independent and the needs of each district matching organisation. Nevertheless, the concept fails in reason of the continuing centralised financial resources that are still held by the mayor of the city.

2.3.2 The water war of Cochabamba

The access to safe drinking water sources varies from city to city in Bolivia (Hailu et al., 2012). The water sector in La Paz and El Alto is privatized and it was observed that, after being connected to the drinking water pipes, the access for poor people was facilitated. Contrary, in Cochabamba, the privatization of SEMAPA (Servicio municipal de agua potable y alcantarillado sanitario) led to increased prices and decreased service causing a period between 1999 - 2000 known as the water war of Cochabamba (Escurra et al., 2014). The people fought for water and for the lowering of the water price by marching on the streets of Cochabamba (Carmen Ledo, 2002) (see Figure 12). Even the ones receiving water from a different company were protesting, either because they did not know that they are not affected, or they wanted to defend the price and suppress injustice.

Figure 12: Demonstration on the streets of Cochabamba during the water war in 1999. *Source: Photo by Tom Kruse (1999). Retrieved on 23/08/18 from https://democracyctr.org/article/bolivia-15-years-on-from-the-water-war/*

After the water war, SEMAPA returned to be a public company regulated by the municipality and provides water and sewage services to its residents (Carmen Ledo, 2002). The principles changed after the water war and the conclusion drawn from this tragedy was that there cannot be earned money with the provision of water.

2.3.3 Unequal provision of drinking water and sanitation services in Cochabamba

Baer (2015) questions whether the required infrastructure to connect the households to the present wastewater system could be provided at the same speed as a city grows and identified the lack of resources as the greatest challenge. This finding is supported by Carmen Ledo (2002) who assessed that a gap between low- and high-income population can be seen by comparing the south to the north of the city of Cochabamba: in the south, the people do often not have access to drinking water nor sanitation services, and are repeatedly forced to buy water of insufficient quality from vendors due to exclusion from the municipal service for potable water and sewage (SEMAPA) (Wutich et al., 2016). In line with this, the consumption of water by residents in the north was found to be various times higher than by those in the south. To be born in the south means that your average life expectancy is 20 year less than in the north, caused by the high risk of infant mortality also due to no, or contaminated water (Carmen Ledo, 2002). Deteriorating the situation, the sewage system of the city is connected to 93 % of households in the north and central part of the city, while 86 % of the households are not connected and hence, only 14 % of the wastewater is treated in the south.

2.4 Wastewater treatment systems

A sanitation system consists of several sections that have inter- and intra-sectional dependencies and are influenced by external factors. The treatment of wastewater starts at the household level and ends in the return to the environment by release to the recipient water or reuse (Tilley et al., 2014).

The type of user interface in a developing country strongly depends on the size of the system, but also on cultural and social values that may lead to disapproval (Verbyla et al., 2013) and hence, to the malfunction of the system. The choice is influenced by the availability of resources to construct and to operate the technology, the existing or planned follow-up treatment of the wastewater generated, and if the users accept the solution (Tilley et al., 2014). Some examples of user interface technologies are the following: dry toilets, urinals, pour-flush toilets, cistern flush toilets and urine diverting toilets. All of those have their advantages and disadvantages, e.g. a dry toilet or a urine might be appropriate in water-scarce countries due to the low water consumption, but the release of odour might lead to disapproval by the society. Contrary, flush toilets are widely accepted; however, the initial costs are high, and the operating costs increase with higher consumption of water.

A safe sanitation system relies on the appropriate collection and storage of the generated wastewater products. This step is strongly dependent on the type of installed user interface and accordingly the composition of the input, but also on factors as the requirement of space by the technology, the affordability and the purpose of the output because some solutions serve only to collect and store while others also contribute to the treatment of the sewage. Moreover, the simplicity and robustness are generally essential in developing countries to ensure the adequate O&M. The next step consists of the transportation of the products from the place of generation or storage to the treatment facilities or the place of further usage. There are two ways to transport the sewage: by constructing sewage systems or by using containers that need to be transported by vessels and operated by workers. Before the implementation, the type and the amount of sewage that needs to be transported must be considered as well as the topographic characteristics and the distance from pick-up location to the facility. Furthermore, the risk for society's health and the negative impact on the environment through leakages or spills must be as low as possible.

The wastewater is treated either in centralised wastewater treatment facilities or in decentralised systems. The former is usually implemented for large incoming flows. The treatment is advanced, and pathogens, nutrients and organics can be removed efficiently and hence, improved effluent qualities can be achieved. The implemented technologies come along with the consumption of resources and therefore, the affordability and availability of skilled staff is a requirement. Decentralised or semi-decentralised systems are characterized by reduced complexity and hence, simpler

O&M (Massoud et al., 2009). Additionally, the previous step of transportation is omitted or strongly facilitated due to a treatment close to the point of generation.

The final step is the discharge or the reuse of the effluent or of by-products (e.g. sludge) generated during the treatment process. The various options for reusing or disposing of the end-product require different levels of effluent quality. For the release to a recipient water body or for irrigational purposes, the wastewater must have a certain quality to prevent harm to the environment and human health.

2.4.1 Decentralised wastewater treatment systems

There are different ways a wastewater treatment system can be organized – centralised (see Figure 13 A), decentralised (see Figure 13 B) or a combination of both (Massoud et al., 2009). Even though the implementation of a centralized system may be easier, it was revealed, that centralized wastewater treatment WWTPs in developing countries fail due to high costs and missing expertise for management, operation and maintenance (Parkinson, 2003; Massoud et al., 2009). Decentralized systems have lower construction cost and also the maintenance and operation of the systems are generally cheaper. One major contribution in lowering the cost is the absence of transportation in form of pumps or trucks. Therefore, they are considered as an affordable and reliable alternative for wastewater treatment in developing countries (Libralato et al., 2012). Additionally, experience shows that the needs of the community and the availability of resources when implementing a centralised system were repeatedly ignored (Massoud et al., 2009).

Decentralised systems are considered to be cost-effective and adequate long-term solutions to meet the sustainability goals (Massoud et al., 2009). One reason is the involvement of local government and stakeholders to meet the needs of the community and to protect the local environment. The residents become more aware of the importance of the treatment and are expected to have a higher willingness to pay. It is common that the residents do not know about the risks of releasing the untreated wastewater and the direct contact forces them to look into this subject. However, since centralised systems are often located out of sight, society is more willing to accept the WWTP with all its emissions, because they are not directly affected, whereas, in a decentralized system, the WWTP has a direct impact on the everyday life of the residents.

Another advantage of decentralized systems is the reuse of wastewater close to the point of source and the chance for the improvement of the economic situation of local farmers due to higher food production and decreased freshwater consumption (Parkinson, 2003). From this, the entire community may benefit as more water is available and workplaces may be created.

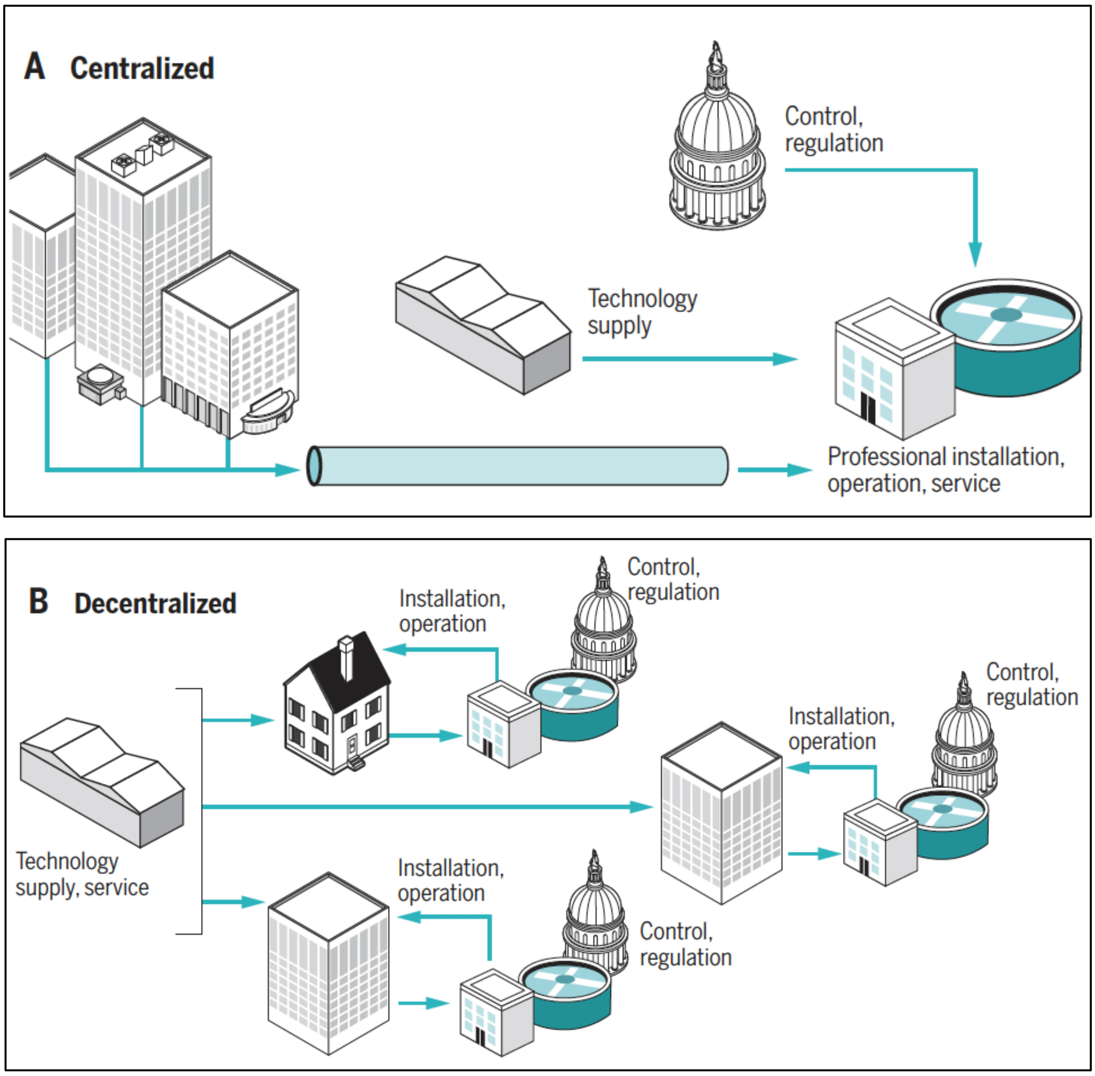
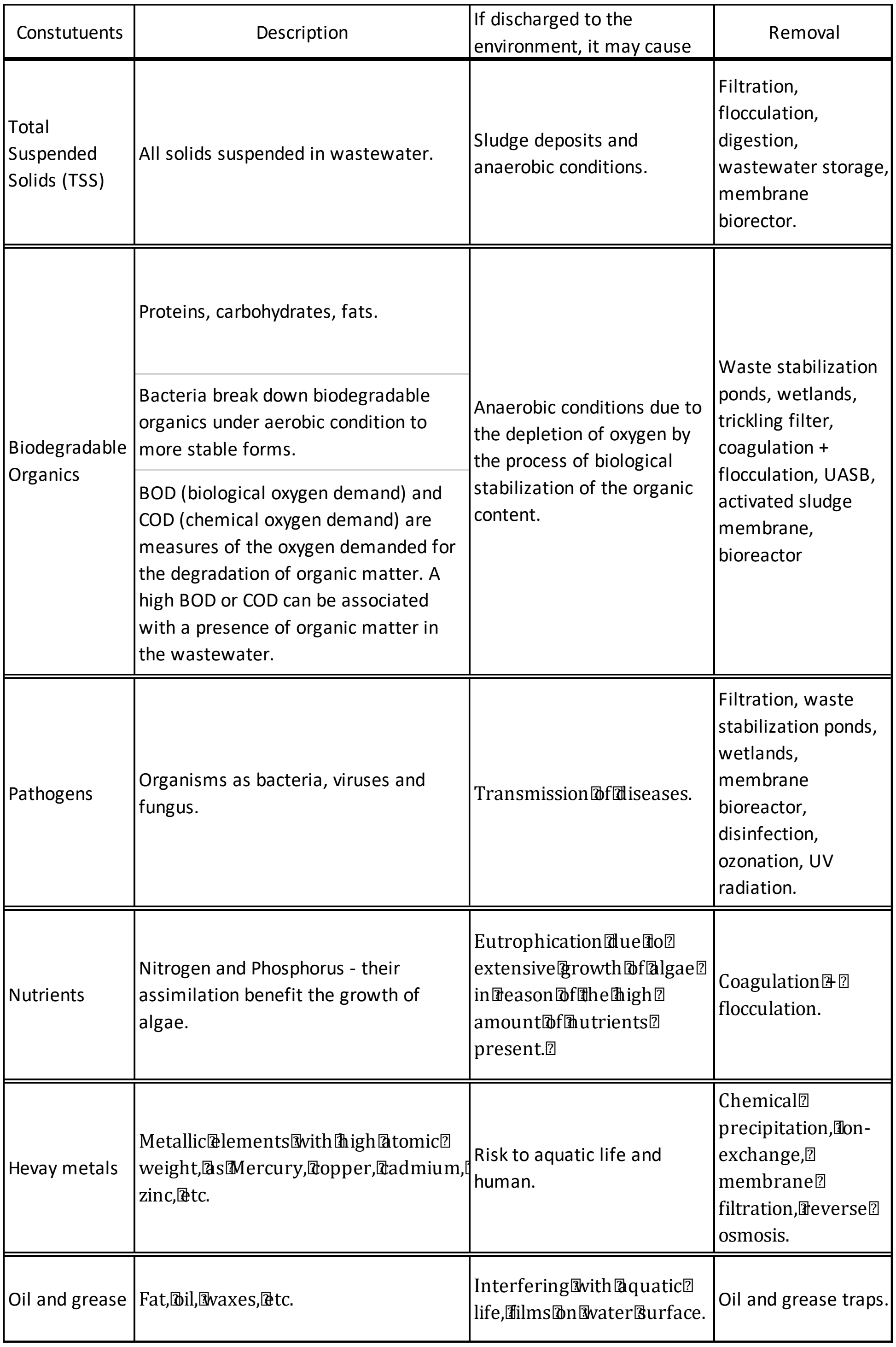


Figure 13: Model of a centralised (on top) and decentralised (on bottom) treatment system. *Source: Larsen et al. (2016). Retrieved on 23/08/2018 from http://science.sciencemag.org/*

2.4.2 Wastewater constituents

There are different types of wastewater: domestic and industrial wastewater (Odlare, 2014). These two combined are called municipal wastewater. Accordingly, the composition of wastewater can vary depending on the source. However, wastewater is typically composed, by weight, of 99,9 % water and 0,1 % other compounds; and the ladder requires the need for treatment before the wastewater is discharged to the environment (Buchanan, 2011). It consists of organic and inorganic matter and microorganisms and the purpose of WWTPs is to remove these constituents from wastewater according to the given requirements for the effluent quality (Bahadori and Smith, 2016). The most important pollutants are called primary pollutants and are considered to pose a risk to the environment and society (Tchobanoglous et al., 2003). In the following *Table 1*, a list of in this report relevant the wastewater constituents is presented, including a short description.

Table 1: Selection of constituents of wastewater. Source: Tchobanoglous et al. (2003), Bahadori and Smith (2016), Jiménez et al. (2010), Spellman (2013) and Buchanan (2011), Laugessen and Fryd (2010), Ahluwalia and Goyal (2007).



Constutuents	Description	If discharged to the environment, it may cause	Removal
Total Suspended Solids (TSS)	All solids suspended in wastewater.	Sludge deposits and anaerobic conditions.	Filtration, flocculation, digestion, wastewater storage, membrane biorector.
Biodegradable Organics	Proteins, carbohydrates, fats. Bacteria break down biodegradable organics under aerobic condition to more stable forms. BOD (biological oxygen demand) and COD (chemical oxygen demand) are measures of the oxygen demanded for the degradation of organic matter. A high BOD or COD can be associated with a presence of organic matter in the wastewater.	Anaerobic conditions due to the depletion of oxygen by the process of biological stabilization of the organic content.	Waste stabilization ponds, wetlands, trickling filter, coagulation + flocculation, UASB, activated sludge membrane, bioreactor
Pathogens	Organisms as bacteria, viruses and fungus.	Transmission of diseases.	Filtration, waste stabilization ponds, wetlands, membrane bioreactor, disinfection, ozonation, UV radiation.
Nutrients	Nitrogen and Phosphorus - their assimilation benefit the growth of algae.	Eutrophication due to extensive growth of algae in reason of the high amount of nutrients present.	Coagulation + flocculation.
Hevay metals	Metallic elements with high atomic weight, as Mercury, copper, cadmium, zinc, etc.	Risk to aquatic life and human.	Chemical precipitation, ion-exchange, membrane filtration, reverse osmosis.
Oil and grease	Fat, oil, waxes, etc.	Interfering with aquatic life, films on water surface.	Oil and grease traps.

2.4.3 Wastewater treatment technologies

Even though the produced amount of wastewater in small cities in developing countries may be high enough to reason the implementation of a centralised system with sewer collection and a mechanised treatment, they usually lack resources to operate the

WWTP (Verbyla et al., 2013). Due to the high consumption of energy, resulting in higher operational cost, mechanised treatment technologies are only implemented for large incoming wastewater flows in industrialized urban areas (Massoud et al., 2009).

Up-flow anaerobic sludge blankets (UASB) are more advanced and were introduced in countries with higher average temperatures; e.g. in Bolivia, the technology was implemented in the tropical region (Symonds et al., 2014). The advantage in terms of sustainability is that biogas can be recovered; however, the removal of pathogens is low and is commonly achieved by maturation ponds.

As a secondary treatment, wetlands are popular to be implemented in wastewater treatment systems in developing countries due to its affordability. This is in reason of the low cost for construction and also because O&M is not complicated to execute.

In Bolivia, as in many developing countries, stabilization ponds are widely used for wastewater treatment (Symonds et al., 2014). These systems are characterized by a simple configuration in the form of a facultative pond followed by maturation ponds. In these ponds, reactions triggered by the sunlight and complex microbial mechanisms are used to reduce, within the facultative ponds, the biochemical oxygen demand (BOD) and the total suspended solids, and to remove, within the maturation ponds, the pathogens.

Treatment technologies relevant for this work

In this section, the concept of the technologies implemented in the two WWTPs are shortly described, but without the consideration of the actual design chosen for the treatment plants.

Pre-treatment

The first unit of a WWTP is the pre-treatment and consists of technologies using physical forces, as screening, aeration and sedimentation to remove inorganic solids from the liquid (Tchobanoglous et al., 2003; Bahadori and Smith, 2016). This process step has the purpose to ensure the performance of the following treatment processes and to prohibit any harm of the equipment.

An efficient pre-treatment can remove up to 70 % of the suspended solids and the primary effluent may have a BOD content reduced by 40 %. Other components of the wastewater that should be removed are oil and grease.

Screens

The incoming wastewater passes commonly one screen or several screens in series with reducing openings to remove larger objects and matter (Tchobanoglous et al., 2003). The design of the screens can vary in form, as the metal bars can be orientated parallel or in meshes. The openings often have a rectangular or circular shape and their size determines the number of solids that will be removed.

Sedimentation tank

After the removal of coarse solids by screening, the wastewater enters a sedimentation tank (see Figure 14), also called clarifier or settler (Tchobanoglous et al., 2003). The main purpose is to remove BOD and TSS from the wastewater stream. The design of the basins, most commonly rectangular or circular, depends on the size of the treatment plant and on other factors. To ensure a continuous treatment process during maintenance, at least two tanks should be implemented.

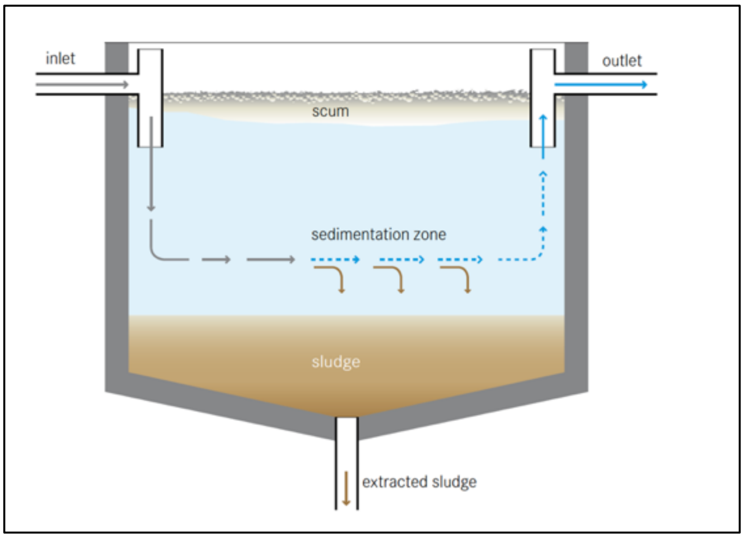


Figure 14: Schematic sketch of a settler. *Source: Tilley et al. (2014).*

Here, it must be retained for a certain amount of time to ensure the removal of suspended organic solids due to the settling of the particles heavier than water according to Newton, for the turbulent region, and Stokes, for the laminar region.

The interfering forces are the gravitational force, the lifting force and the friction force (Shukla, 2013). These three forces are in an equilibrium after the particle reached its maximum settling velocity:

$$F_g = F_l F_d \;<=>\; F_g - F_l = F_d \qquad (1)$$

with the gravitational force $F_g = V_p \rho_p g \; [\frac{kg*m}{s^2}]$, the lifting force $F_l = V_p \rho_w g \; [\frac{kg*m}{s^2}]$, the frictional drag force $F_d = \frac{C_d A_p \rho_w v_p^2}{2} \; [\frac{kg*m}{s^2}]$, where V_p is the volume of the particle $[m^3]$, the density of the particles ρ_p $\left[\frac{kg}{m^3}\right]$, the density of the water ρ_w $\left[\frac{kg}{m^3}\right]$, the acceleration of gravity g $\left[\frac{m^2}{s}\right]$, the drag coefficient $[-]$which is dependent on the Reynolds number, the cross-sectional area of particles in direction of flow $[m^2]$, and the settling velocity v_p $\left[\frac{m}{s}\right]$, which results to be $v_p = \sqrt{\frac{4g}{3C_d}\left(\frac{\rho_p-\rho_w}{\rho_w}\right)d_p}$ (Tchobanoglous et al., 2003). For Re<1.0, Stoke´s law can be used to formulate the settling velocity (Stokes, 1850):

$$v_p = \frac{g(\rho_p - \rho_w)}{18\eta} d_p^2 \qquad (2)$$

with the dynamic viscosity $\eta\ \left[\frac{kg}{m*s}\right]$. Accordingly, given constant conditions, larger particles settle first because the settling velocity of the particle is proportional to the square of its effective diameter.

Primary treatment

During the primary treatment, the remaining dissolved and suspended material is removed in a biological sewage treatment process (Bahadori and Smith, 2016). Making use of microbiological processes, the soluble organic matter can be separated from the water.

Up-flow Anaerobic Sludge Blanket Reactor (UASB)

The functioning of a UASB reactor is a based on the growth of a sludge blanket composed of microorganisms that form agglomerates and are not washed out due to their weight (Tilley et al., 2014), i.e. hydrodynamically suspended sludge (Bahadori and Smith, 2016). The wastewater is entering the reactor is there distributed on the bottom surface (see Figure 15 to follow the process). The up-flow, with a recommended velocity of 0.7 to 1 m/h that should be maintained, makes it pass the SB and the contained organic compounds are degraded and hereby, the BOD is reduced significantly (Bdour, 2007). This leads to the by-product of biogas, which rises in form of bubbles and by doing this, the sludge is mixed (Tilley et al., 2014). The gas, then, leaves the reactor at the top and is either captured to reuse or is burned directly. The effluent exit is located on the top of the reactor.

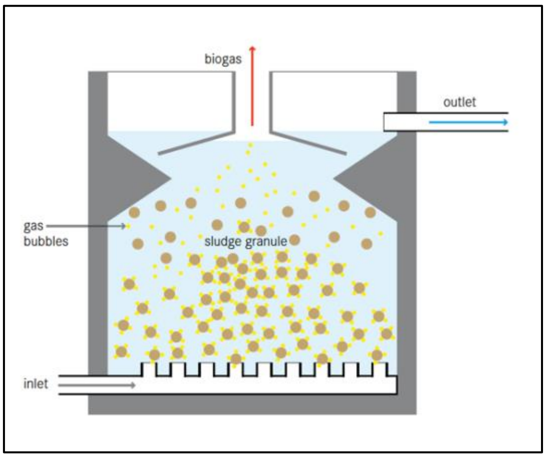


Figure 15: Schematic sketch of a UASB reactor. *Source: Tilley et al. (2014).*

The anaerobic treatment process provides advantages and disadvantages for a wastewater treatment plant (Tchobanoglous et al., 2002). One major advantage is the reduced consumption of energy, the reduced amount of produced biological sludge, the potential for using produced gases as an energy source, the reduced volume for the required reactor. However, there occurs no removal of nutrients as phosphorus and nitrogen and follow-up treatment under aerobic conditions may be needed to meet the required effluent quality. The temperature plays an important role due to the growth rate of microbiological organisms and lower temperatures may impact the performance of the treatment (Seghezzo et al., 1998). Before the treatment can begin, time is needed until a sufficient layer of biomass is produced. Another factor, that may be considered negative, especially in urban areas, is the release of odour.

A necessity to make this technology work is the continuing flow of incoming wastewater (Tilley et al., 2014). Without, the sludge blanket is damaged, and the organic compounds may not be removed sufficiently.

Secondary treatment

The biodegradable organic matter, as well as suspended solids maintaining in the primary wastewater effluent, are removed during the secondary treatment step (Bahadori and Smith, 2016).

Horizontal subsurface flow constructed wetland

To reduce the BOD, the content of suspended solids and nitrogen in the water, constructed wetlands (see Figure 16) can be used (Bahadori and Smith, 2016). Anaerobic and facultative bacteria attach to the filter medium’s surface and the wastewater is cleaned through the degradation of organics and the removal of solids by filtration (Tilley et al., 2014). The plants, often native species, are used to create an aerobic zone around the roots to increase the removal of organics by additional degradation by aerobic bacteria.

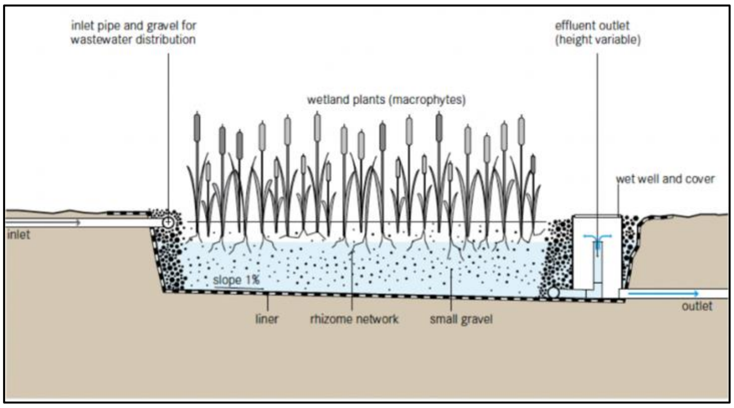


Figure 16: Illustration of a constructed wetland with horizontal flow. *Source: Tilley et al. (2014).*

The design is characterized by a basin filled with sand and gravel and plants growing on the surface and it is bordered by an impermeable layer to prohibit the contamination of soil and groundwater. As can be seen in Figure 16, the wastewater coming from the primary treatment enters the basin over a pipe and is first distributed by passing a layer of gravel. It then passes horizontally through the filling of gravel and sand due to a slope of about 1 %. The amount of wastewater that can be treated can be increased by increasing the cross-sectional area. Depending on the surface area, different removal efficiency can be achieved. Therefore, the availability and affordability of land is a factor influencing the decision of implementing this technology in the wastewater treatment system and makes it especially interesting for decentralised systems in peri-urban or rural areas. The O&M of this technology are considered to be simple and low-work-intense. If the previous treatments fail at sufficient removal of solids, clogging may cause problems. Especially, when sand is used as filter material there exist a higher risk. The filter medium must be exchanged when clogged. However, this can be avoided for long periods if it is taken care of that pre- and primary treatment work efficiently. Furthermore, the growth of plants must be controlled. To keep the horizontal flow, a constant water level of 5 to 15 cm is recommended. Due to the flow below the surface, there does not exist any direct contact with humans and therefore, the health risk for WWTP operators is very low.

Anaerobic filter

The anaerobic filter is a treatment technology is suitable for any type of treatment system (Tilley et al., 2014). The design can vary from one to more chambers in series that all must be accessible for maintenance (see Figure 17). It can be adjusted by adding a sedimentation chamber before to reduce the number of solids entering the filter media. The most important factor is the hydraulic retention time that is recommended to be 12 to 36 hours. Before the filter can operate, the biomass needs to be formed and this can take up to 9 months. Under anaerobic conditions, bacteria attach to the surface area of the filter material and form an anaerobic biomass that degrades organic matter contained in the wastewater that passes through the filter. The removal of BOD and suspended solids is high, up to 90 %, but the removal of nutrients, as well as pathogens, is low. Gravel and crushed rocks with a size between 12 and 55 mm are appropriate as filter materials, since their surface area is large, and the formed pores provide sufficient space and hence, reduce the risk of clogging. However, a highly efficient pre- and primary treatment is required to make this technology work without the requirement of advanced maintenance skills. During normal operation, there is no direct contact required, but for desludging and for cleaning the filter, once it is clogged and shows reduced treatment efficiency, it is important to work with caution since wastewater and sludge are high in concentration of pathogens. The effluent required further treatment and cannot be discharged directly to the recipient water.

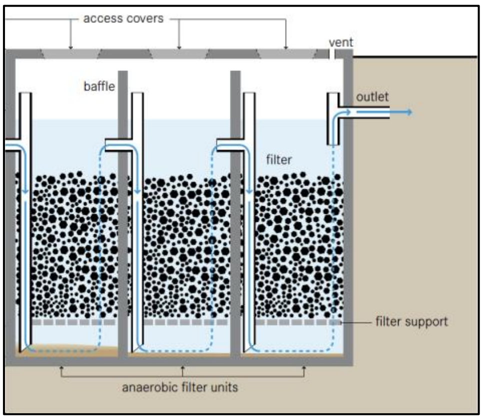


Figure 17: Illustration of an anaerobic filter as part of the secondary treatment unit. *Source: Tilley et al. (2014).*

The main advantages are the low operating costs due to the lack of electricity consumption, the efficient removal of BOD and suspended solids, the low production of sludge. To benefit from these, the filter must be designed and build properly. Moreover, clogging is the main contributor to reduced performance leading to increased maintenance in form of more frequent need of cleaning. To prevent this, the previous treatment steps must yield for a high removal of solids.

Tertiary treatment

In the tertiary treatment step, organic and inorganic material remaining in the wastewater after the conventional treatment steps is removed, e.g. nutrients and suspended solids (Bahadori and Smith., 2016). Often, treatment technologies are included that treat the water to a level sufficient for being reused, depending on the purpose of the reuse.

Waste stabilization pond (Maturation pond - aerobic waste stabilization pond)

There are three different types of waste stabilization ponds, of which one is a maturation pond: an artificial waterbody, that is separated from the groundwater by an impermeable layer, with aerobic conditions (see Figure 18) (Tilley et al., 2014). The excavated material can be used to build a small dyke around the basin to prevent runoffs. A requirement for the implementation of waste stabilization ponds is the availability of land.

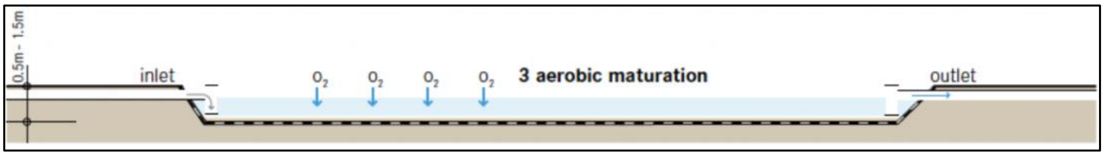


Figure 18: Maturation pond. *Source: Tilley et al. (2014).*

The depth of a maturation pond normally does not exceed 1.5 m, allowing photosynthesis to take place over the entire depth. The remaining organic matter is biologically oxidised. Photosynthetic algae consume the carbon dioxide produced by bacteria and release oxygen. Besides the reduction of BOD, also solids and pathogens are removed. Furthermore, it can be operated in combination with aquaculture and then, then it offers a very efficient nutrient removal.

In order to ensure a continuing functioning of the pond, the foregoing treatment steps must be efficient in removing solids. External contamination through animals, people and garbage must be avoided. Scum can accumulate on the surface as well as growing plants must be removed frequently, because it may hinder the sunlight to pass.

Sludge treatment

During secondary and tertiary treatment of wastewater, the removed suspended solids accumulate and form the sludge (Bahadori and Smith, 2016). Sludge contains water and biosolids and can be treated in various ways, e.g. it can be reused or disposed. The dewatering serves to facilitate the further handling of the sludge by reducing its weight and volume. However, no removal of pathogens takes place, nor is the sludge stabilized (Tilley et al., 2014).

Drying beds

The dewatering of sludge can be achieved by implementing drying beds (see Figure 19) where the water contained drains through a medium or it evaporates (Bahadori and Smith, 2016), what dries the sludge by 50 to 80 %.

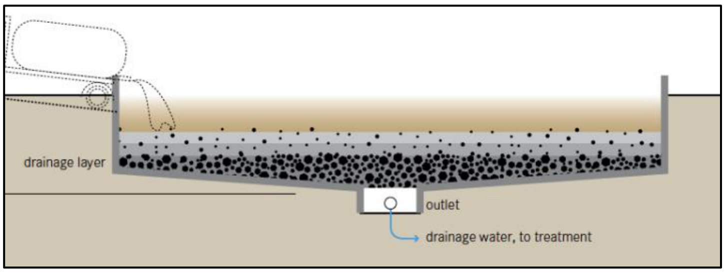


Figure 19: Concept of drying beds. *Source: Tilley et al. (2014).*

The sludge is spread over a surface, consisting of permeable material, and the thickness should not exceed 20 cm to ensure the effective drying (Tilley et al., 2014). The leachate is collected in drainage pipes below the bed. Further treatment is required before it can be discharged. To transport the dried sludge, it must be removed from the surface. The disadvantage of drying beds is the production of odour as well as the presence of flies. In case of rain events, the bed must be covered to avoid the additional moisture in the sludge. Apart from that, the process does not need further alertness.

2.5 Sustainability of wastewater treatment systems

The principle of sustainability is the base for this work and it is described carefully and extensively in this section which also includes the concept of sustainable development indicators (SDIs).

Definition of sustainability

In 1987, the World Commission on the Environment and Development published the to this day most famous definition of sustainability: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Since then, many variations of this definition were formulated by researchers and Muga and Mihelcic (2008) attribute sustainability with the meaning of the maintenance or, desirably, the improvement of the current situation by triggering the economic prosperity, ensuring society's well-being and respecting its values, and preserving the environment. Accordingly, it demands the use of a resource without depleting it but ensuring its availability in the future (Bradley, 2002).

The foundation for assessing any system in terms of its sustainability is the definition of what is considered as a sustainable solution. As stated by many scientists, there exists no clear definition since there is no standard in form of a value that indicates if a system is sustainable (Hellström et al., 2000). The attempt, therefore, is to rather describe what sustainable development yields for. The goal of "improving the quality of human life while living within the carrying capacity of supporting ecosystems" (WWF, 1991) is the major focus in a sustainable decision-making process. This means that an important factor lies in a long-term consideration of the effect on the well-being of future generations.

There exist three dimensions of sustainability: societal, environmental and economic sustainability (Muga and Mihelcic, 2008). These dimensions are closely connected and a direct influence on each other can be easily be observed. In Figure 20, the overlap of all three dimensions is where sustainability takes place. If only the sphere between two of the dimensions is fulfilled, the third dimension is left out (Slocum, 2015). Hence, the space between social and environmental dimension is bearable but does not provide economic benefits, the one between social and economic is equitable but may cause harm to the environment and the one between environment and economic is viable but neglecting the social aspect.

A sustainable solution leads to the improvement of many factors without causing a significant negative impact on others. Rarely, the solution only has positive effects, nevertheless, the overall outcome must be equally beneficial and must not violate one of the dimensions to the greater benefit of another. The goal to meet societies needs incorporates the improvement of the current living standards and prevention of cultural values, having the lowest possible impact on the environment while being feasible in a long-term perspective (Singhirunnusorn and Stenstrom, 2009).

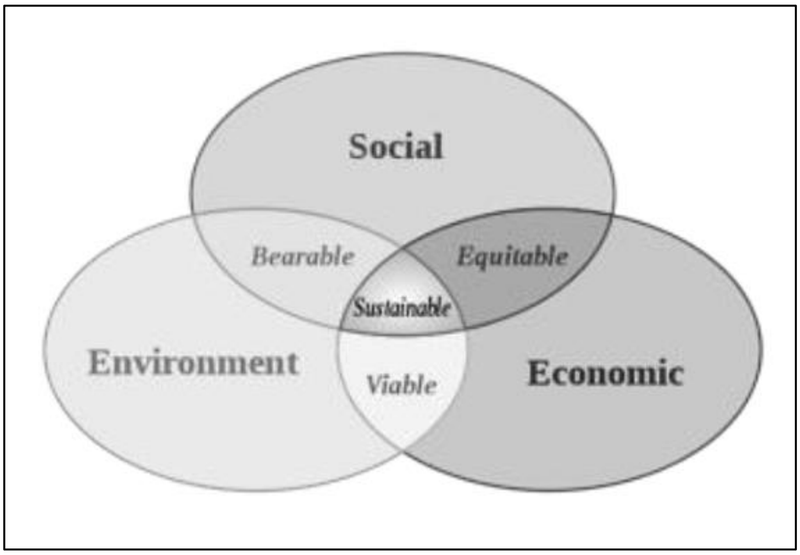


Figure 20: The three dimensions of sustainability. *Source: Roxendal (2012).*

2.5.1 Sustainability in the context of wastewater treatment systems

The cleaning of wastewater before discharging to a river comes along with costs for the process, decreased impact on the environment by removing pathogens and nutrients from the water, which improves the health situation of the local society, as well as reduces the costs of cleaning the water if used downstream as drinking water source; but also has another economic benefit in form of creation of workspaces and therefore, decreased unemployment. Furthermore, and due to a better health situation, fewer cases of diseases and fewer costs for health care. Hence, the dimensional influences within a wastewater treatment system are complex and various factors must be taken into account in sustainable decision-making (Hellström, 2000).

Suggested by Andersson et al. (2016), the sustainability of wastewater system must be, in the first place, based on resource management and should cover the

- Financial
- Technical
- Environmental,
- Social and health protection,
- Institutional sustainability.

The concept of sustainability applied to wastewater systems is the protection of human health, the recovery of natural resources and the prevention of their depletion, and therefore, the prevention of negative impacts on the environment. Sustainable wastewater systems should be efficient as well as economically viable in a long-term while entailing the support by the society.

The great amount of wastewater discharged to the environment has a negative impact on the environment and moreover, related health problems cannot be excluded (Andersson et al., 2016). A strong relationship between a functioning wastewater system and the accomplishment of higher living standards was reported the literature (Muga and Mihelcic, 2008). Nevertheless, it is important to bear in mind that the implementation of a wastewater treatment system does not yield necessarily to an improvement of the overall situation if not well-planned. An often-appearing problem within developing countries is the malfunction of systems due to the implementation of sophisticated technologies and a lack of qualified staff (Singhirunnsorn and Stenstrom, 2009). As stated by Fogelberg (2013), 40 % of projects related to water are malfunctioning due to a lack of proper management, lack of support by governance and missing participation of the society. Hence, the system relies on being well maintained and operated, which means that monitoring must be implemented and instructions for the workers must be provided. A different cause of malfunctioning was identified by Andersson et al. (2016) to be the negligence of cultural values and consequently, the missing acceptance and support by society lead to wrong interface usage.

Especially in small cities in developing countries, a growth of population is expected, resulting in higher wastewater flows (Verbyla et al.,2013). With respect to this, appropriate planning of wastewater systems includes to meet or to provide the possibility to meet future generations' needs. Thus, governments, policy-makers and local stakeholders must work together toward sustainable solutions with respect to societies' perspectives.

Among many other researchers, Andersson et al. emphasize the consideration of wastewater as a resource to enhance the economic, social and environmental situation of a region or respectively of a country. In line with this, the option of wastewater reuse for irrigation is favourable and supported by the fact that 70 % of the amount of extracted freshwater is currently used for irrigational purpose (Sustainable Development Solutions Network, 2016) and therefore, is used in an unsustainable manner (Ridoutt and Pfister, 2010). Moreover, the process of removing nutrients from the wastewater to a sufficient level to release it to the recipient water body is resource consuming (Verbyla et al., 2013).

Sustainable Development Goal 6

A change in water consumption activities towards a greater sustainability is requested by *Goal 6* of the Sustainable Development Goals (see Figure 21), accompanied by the protection of water-related ecosystems (Sustainable Development Solutions Network, 2016). Furthermore, the goal demands "halving the proportion of untreated wastewater and substantially increasing recycling and safe use globally" (Sustainable Development Solutions Network, 2016).

This goal is of high significance due to its impact on health as well as the environment, e.g. in form of harming ecosystems and decreasing biodiversity. Accordingly, all wastewater must be treated to a sufficient quality to be returned to the water body or recycled and to produce sludge that can be reused, e.g. for the irrigational purpose, or be deposited.

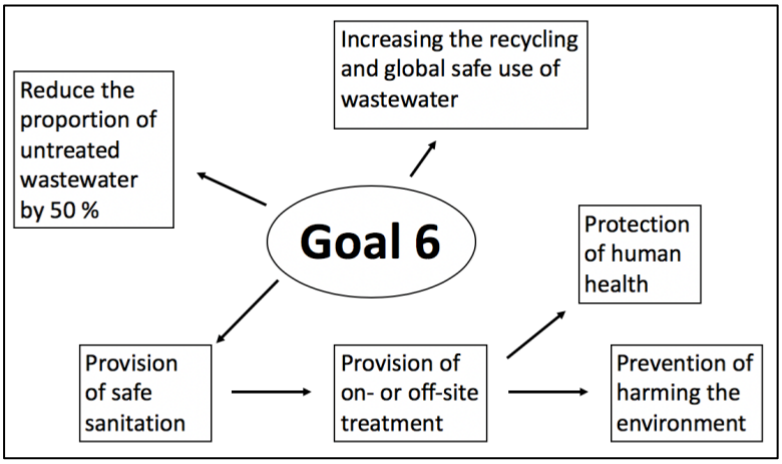
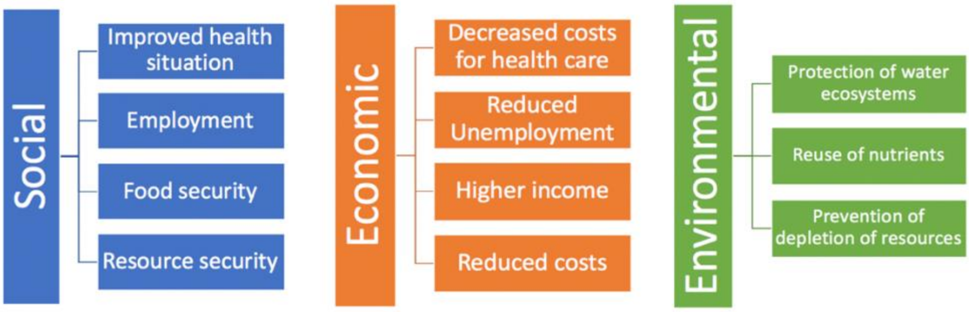


Figure 21: Objectives addressed by Goal 6 of the Sustainability Development Goals.

A list of indicators describes the goal more closely: *Indicator 46* covers the urge to provide safe sanitation which includes the prevention of untreated wastewater harming the environment by ensuring on- or off-site treatment of household excreta, and *Indicator 47* addresses respectively the treatment of both domestic and industrial wastewater.

The benefits coming along with a sustainable wastewater management are visible within all three dimensions and can be described in a brief concept as followed:



The major advantages for society are given by an improved health situation due to safe water quality, a higher employment rate due to a better economy and food security due to an increased agricultural productivity, the environmental protection which comes along with the prevention of resource depletion and recreational value.

The economy of the country benefits due to the decreased costs for health care, a higher income due to improved agricultural productivity and hence, a better soil quality, fewer failures due to an enhanced management as well as reduced costs due to the lower energy consumption and the recycling of resources.

The environment plays a crucial role since it provides the resources humans depend on to survive. Some resources are not vital, although, to ensure the ongoing prosperity and therefore, offering the same living standard to future generations, the reuse of resources and the prevention of depletion is a major concern when planning sustainable. Protecting the ecosystems on earth is necessary to maintain the resource flows. Everything in nature is connected and the harm to one part causes the harm of another. This is why sustainable wastewater treatment will protect the soil quality, reduce the negative impact on the recipient water, reduce the energy consumption and might even provide energy, and the reduced GHG emissions decreases the impact on the climate.

2.5.2 Sustainable development indicators

The planning of a wastewater treatment system is time intensive due to the high number of factors that must be considered (Singhirunnusorn and Stenstrom, 2009). The initial phase, in which different solutions are evaluated and selected, is considered the most demanding one. A significant improvement and facilitation could be provided by implementing a decision-making model for a holistic assessment based on indicators relevant to the local conditions. In developing countries, this would give the opportunity to provide sustainable wastewater management from the beginning of projects by the support in the decision-making process through those indicators. Moreover, according to Palme et al. (2005), they can be used as a tool for “reporting, planning, control, benchmarking and formulation of targets”. The potential benefits are a higher reliability and efficiency of the system due to more adequate O&M, the acceptance by the society and the long-term affordability, the recovery of resources and the prevention of their depletion, and therefore, fewer failures that again results in the protection of health, the environment and economic growth by providing highest performance at lowest reasonable costs (Singhirunnusorn and Stenstrom, 2009).

Assessment of sustainable development indicators

To form the fundament for a holistic assessment within a decision process, the criteria and indicators must be defined clearly to reduce the limitations of the ranking method (Molinos-Senante et al., 2015).

Palme et al. (2005) provide a conceptual model for the procedure of formulating a set of sustainable development indicators (SDIs) for a case study concerning sludge handling provided by the Stockholm Water Company (see Figure 22). The first step is the clarification of the reasons to use SDIs, the setting of the system boundaries and the selection of options of choice. The system must be described in detail to develop the indicators. Then, the selected options are assessed and compared by different kinds of assessments that provide input data to conduct a Multi-Criteria Analysis (MCA). The outcome and the existing indicators and targets are then used to formulate a new set of indicators that again will be discussed and improved. This step repeats until the final set of indicators addressing the targets for the present system are found.

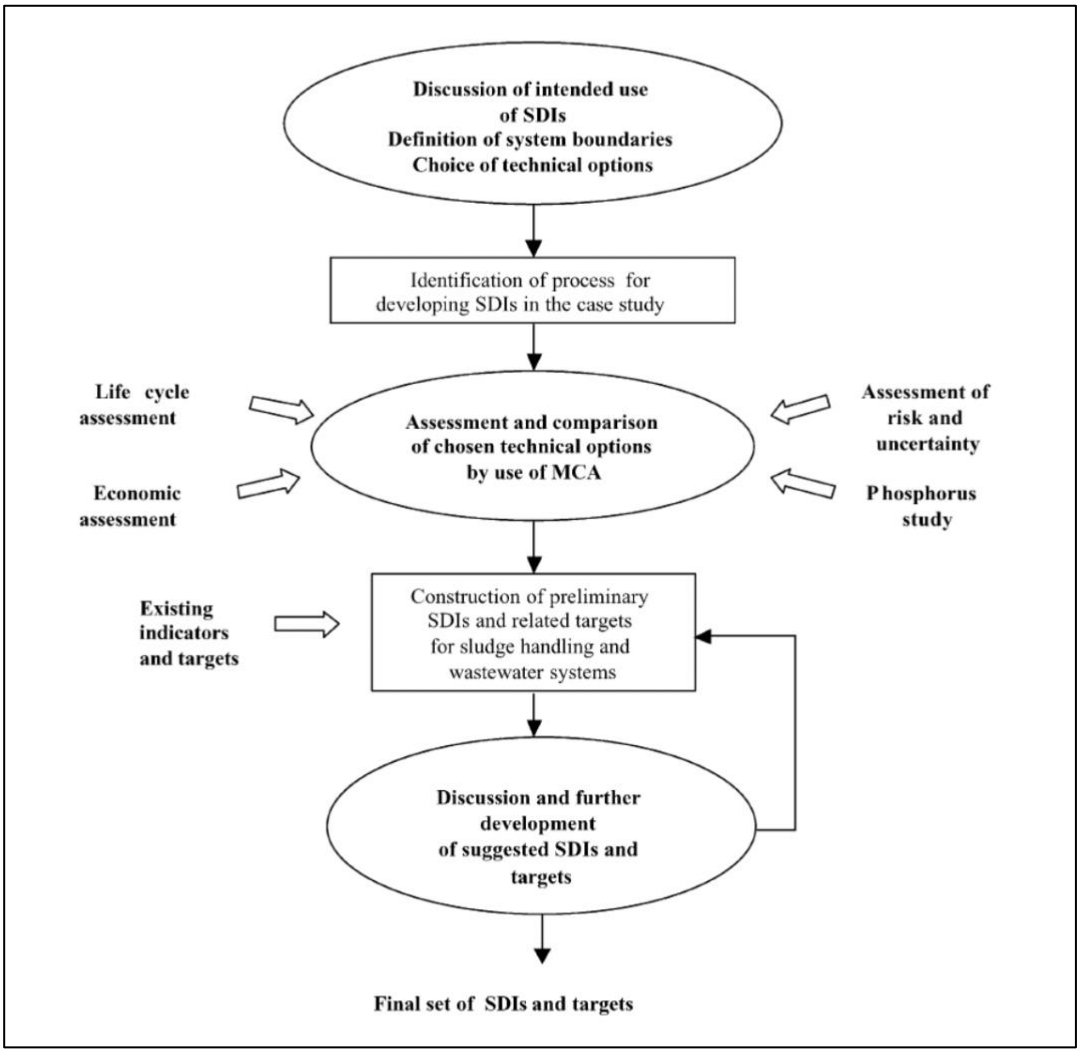


Figure 22: Procedure of the formulation of a final set of SDIs and targets. *Source: Palme et al. (2005)*.

A study, that plays an important role for the final set of indicators of this work, was conducted by Singhirunnusorn and Stenstrom (2009). The tool of MCA was used to formulate a set of criteria and indicators relevant for wastewater treatment systems in Thailand. The indicators, criteria and principles were ranked and rated by experts according to their importance to the respective upper-level group. Hereby, the ranking gave the overall importance of the element while the rating made it possible to reveal its importance within the set of elements. For the rating method, the elements were weighted depending on the importance of the other elements so that the final score accounts for 100 points. The relative weight was then used to compare the results of ranking and rating and to combine the two weights in order to provide an overall weight. The procedure was applied to both the criteria and the indicators. The combined weights of the indicators of one criterion were compared and graphically illustrated to demonstrate the significance against each other. In the case of low weighted elements, the elimination was considered to prohibit unnecessary workload and irrelevant information for the result which should be coherent and comprehensive. However, for this, the elements with low weight were investigated closely with regard to different scenarios reflecting local conditions.

The ranking method

Singhirunnusorn and Stenstrom (2009) found that independently of the usage of ranking or rating the outcome was consistent. In a multi-criteria-decision analysis (MCDA), Saaty's Fundamental Scale (see *Table 2*) can be applied when making use of the analytical hierarchy process (AHP) (Molinos-Senante et al., 2015). The elements (here: indicators) of a certain attribute (here: principle) are ranked against each other in relation to the attribute (Saaty, 2008). The purpose is to facilitate the decision which elements have the highest priorities, and which may be less important and in accordance with the outcome, some indicators can be chosen over others.

Table 2: The fundamental scale of absolute numbers by Saaty (2008).

Intensity of Importance	Definition
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong or demonstrated importance
8	Very, very strong
9	Extreme importance

One drawback of this approach is the heavy workload for a high number of indicators due to the pairwise comparison of the indicators. A second one is the subjectivity and the resulting strong dependency on the group of experts participating in the weighting process (Molinos-Senante et al., 2015).

The dimensions

In the following, the dimensions and the indicators included within them by other researchers are presented. The indicators do not correspond with the set of indicators chosen to investigate the two WWTPs but yield to increase the understanding of what type of indicators are included within each of the five dimensions. The institutional describes the institutional factors incorporated within the other dimensions (Djoghlaf, 2007) and little is found in the literature on its application in case studies.

The economic dimension covers all costs related to the wastewater treatment system (Hellström et al., 2000). Especially in developing countries, it is highly important to ensure the affordability of the system (Singhirunnusorn and Stenstrom, 2009). This means that not only initial costs but also O&M costs in a long-term perspective must be calculated (Molinos-Senante et al., 2014). Furthermore, the monetary amount that can be carried by the system's user and the labour cost must be captured to ensure the continuity of the operation of the treatment plant (Singhirunnusorn and Stenstrom, 2009).

The technical dimension ensures that the system provides the highest efficiency at the lowest cost and the execution of operational duties by qualified staff (Hellström et al., 2000). To achieve sustainability, the system must be flexible for upgrades to meet future needs and stricter requirements (Molinos-Senante et al., 2014). The criterion reliability is the insurance of the continuity of the system's performance over a certain time and covers the mechanical functionality of the system (Singhirunnusorn and Stenstrom, 2009). It must be reliable under normal and extraordinary conditions (e.g. change in the constitution of the incoming wastewater or high flows) and variations must be within certain borders. This applies also in case of failures; however, the risk of failures must be as low as possible. The impact in case of failures on the effluent quality is closely connected to the aspect of environmental sustainability (Molinos-Senante et al., 2014). New technologies are often too advanced to be operated by the local staff and therefore, the simplicity of the system as well as of its components is a crucial factor to consider (Singhirunnusorn and Stenstrom, 2009). This criterion influences directly the reliability of the system due to failures caused by human incompetence. Non-educated workers are cheaper and hence, the initial cost could be reduced by lowering the complexity. However, a higher level of education contributes to sustainable development (Muga and Mihelcic, 2008), although, in this case, the locals might not be the ones operating the WWTP.

The efficiency of the treatment must be high enough to fulfil the requirements which depend on the availability of different recipient waters or if the water is to be reused (Muga and Mihelcic, 2008). To determine the efficiency, samples must be taken and parameters of interest (e.g. organic matter (BOD, COD), TOC, TSS, pathogens, N, P) must be measured and compared to standard values (Singhirunnusorn and Stenstrom, 2009). The release of high concentrations of nutrients contributes to the eutrophication of water bodies and has a negative impact on the quality of groundwater which may be used as drinking water source and therefore, may be a risk to human health (Singhirunnusorn and Stenstrom, 2009). A direct threat to human health is also the discharge of pathogens. To ensure good water quality the organic matter must be removed from the water (Nagwekar, 2014).

The environmental dimension demands the prevention of insufficiently treated wastewater being discharged into the environment, the consideration of local conditions and resources, and the recovery and reuse of resources (Hellström et al., 2000). In other words, the focus is set on the protection of the environment and the conscious use of resources to prohibit their depletion and thus, to ensure the same quality of life to future generations (Balkema et al., 2002). To fulfil the principles within this section, the wastewater system must not only remove toxic compounds to protect water, soil and human health but also ensure the responsible consumption of resources and if possible, their recovery and reuse to sustain the natural system (Hellström et al., 2000). The management of the produced sludge is considered as one indicator of the criterion “Resources” and a proper sludge management contributes to a progress towards sustainability (Molinos-Senante et al., 2014). Heavy metals must not be released into the environment while nutrients as phosphorus must be recovered (Palme et al., 2005). Furthermore, the emission of climate change triggering greenhouse gases (GHG) must be as low as possible (Hellström et al., 2000). The wastewater system must have the lowest impact on the environment while providing the efficiency to fulfil the requirements for the effluent quality. The measurement of energy and water consumption used chemicals and other materials and the emission-related GHG give quantitative data and must be compared to limit or guideline values (Hellström et al., 2000), for example, the energy use must be as low as possible (Palme et al., 2005). The recovery of phosphorus and the reuse of wastewater for in most cases irrigation is beneficial for the environment, for the economy and for the society (Singhirunnusorn and Stenstrom, 2009)**.** Hereby, it is necessary to ensure that all pathogens are removed from the wastewater and that the amount of nutrients recycled is controlled (Palme et al., 2005).

The land requirement is described not only by the size the WWTP occupies and that accordingly cannot be used for other purposes but also by the emission of noise and odour affecting the society which can be reduced by increasing the space between treatment and users (Singhirunnusorn and Stenstrom, 2009).

The principles under the social dimension ask for a low impact on society, which is crucial to ensure the acceptance of the system (Molinos-Senante et al., 2014). This acceptance is influenced by the visual perception, noise and odour emissions, impact on health and the improvement of the overall situation as better water quality, higher production rate due to safe irrigation, and increased number of employment. The aspect of health in relation to wastewater treatment systems is essentially the provision of clean water and safe sanitation to society (Hellström et al., 2000). If insufficiently treated water is released into the environment it might be reused for irrigation or other purposes as washing and this may result in a risk for human health. The risk of infection can be illustrated by counting the number of waterborne outbreaks. Also, related to safety, the risk of an accident at the workplace might be an indicator to consider when planning a treatment plant.

3 Methodology

The Chapter Three describes the various procedures to obtain the desired results and is divided into three main parts with the first covering the methods used to select SDIs (Section 3.1) by giving an introduction on the general assessment of sustainability indicators (Section 3.1.1), and by describing the formulation of a set of indicators (Section 3.1.2) including the selection of indicators for a specific system and the validation of those. The next Section 3.2 consists of the assessment of small WWTPs. The methods used to collect the data as the formulation of questionnaires and the analysis of the wastewater quality are presented in Section 3.2.1. Following this, the procedure to assess the sustainability is described and includes some guideline values (Section 3.2.2). The Section 3.2.3 explains how the comparison of the WWTPs was undertaken. The last section is Section 3.3, addressing the identification of significant indicators within the generated set of SDIs. Here, the applied ranking method and the normalisation approach are explained.

3.1 Selection of sustainable development indicators

The approach used for formulating a set of indicators can be divided into two sections. The first is the assessment of SDIs relevant for wastewater treatment systems in developing countries. The ladder presents the methodology used in this study to formulate the final set of SDIs relevant for Bolivia, and respectively, for the two investigated treatment plants.

3.1.1 Assessment of sustainability indicators

Due to the time-intensive procedure of assessing the indicators by performing multi-criteria decision analyses using tools as life cycle assessments (LCA), economic assessments and risk assessments for the entire span of SDIs, this thesis uses data from previously conducted studies. In the following, the basic principles used in these studies are described.

Balkema et al. (2002) describe the setting of the system's boundaries as the basis for the assessment of SDIs. The sustainability of a system is its social, environmental and economic safety and it is, therefore, crucial to be considered in decision-making processes, in short- and long-term perspectives. The definition of a sustainable wastewater treatment system is the foundation, but it is difficult to define sustainability, as described in Section 2.5. Instead, a hierarchical structure is elaborated where the dimensions of sustainability are represented by principles which again are described by criteria and more detailed by indicators (Singhirunnusorn and Stenstrom, 2009). Weak and strong dependencies between and among the dimensions, principles and criteria were identified by Molinos-Senante et al. (2015).

The method presented by Hellström et al. (2000) is to:

- identify the principles indicating a sustainable wastewater system in developing countries,
- elaborate the criteria, having the purpose to give meaning to the principles,
- define the indicators, giving clear information in form of measurable values of what is required to fulfil the corresponding criterion.

To facilitate the assessment, all indicators should be relevant in terms of sustainability, easy to quantify (i.e. to measure or to obtain from literature), transparent (i.e. clearly described and reasoned why they were chosen) and representative for the criterion (Molinos-Senante et al., 2014). They must be judged to indicate a positive and negative impact, where the first is a movement towards and the ladder a movement away from sustainability. Thus, a high value for a positive indicator is an improvement while for a negative indicator it is a worsening. The targets must be described with caution to ensure the movement into the intended direction (Palme et al., 2005).

3.1.2 Formulating the set of SDIs

The generated set of SDIs was highly influenced by the following studies: Bassan et al. (2014); Bradley et al. (2002); Hellström et al. (2000); Lundin et al. (1999); Molinos-Senante et al. (2014); Muga and Mihelcic (2008); Singhirunnusorn and Stenstrom (2009).

To formulate the set, indicators that address the main principles of sustainability and the situation present in developing countries were chosen from many lists of sustainable indicators provided by the aforesaid studies. The scope of the first set of SDIs is rather wide to provide the possibility of using it at varying locations and for differing conditions.

The selection of indicators for a specific treatment plant

Hellström et al. (2000) point out that there exists a correlation between considering many indicators, resulting in a great amount of data, and the inconsistency of the outcome. Therefore, the most relevant indicators must be selected. The main categories must be represented and hence, it is recommended by experts to select one or more significant indicator per principle. An often-used approach is a multi-criteria-decision analysis (MCDA) for which the criteria and indicators are described clearly (Molinos-Senante et al., 2015). The evaluation yields to identify the indicators significant for the respective geographic and demographic context (Muga and Mihelcic, 2008).

To meet the requirements and address the conditions given at the investigated WWTPs, minor modifications of the first set were made. The “top-down” approach, according to

Lundin (2003), was applied and the involvement of experts was used to gather adequate indicators in accordance with the given conditions. The expert knowledge regarding WWTPs in developing countries of Claudia Cossio, PhD student at the Division of Water Environment Technology at the Chalmers University of Technology, Alvaro Mercado, researcher at the Department of Centro de Aguas y Saneamiento Ambiental (CASA) at the Universidad Mayer de San Simón (UMSS), Jennifer McConville, sanitation researcher at the Swedish University of Agriculture Sciences (SLU), and Sebastien Rauch, professor at the Division of Water Environment Technology at Chalmers University of Technology, was used to complete the set.

In this step, it is relevant to collect information about the current situation at the location of interest. It is important to consider all factors that influence any of the chosen dimensions, as for instance the available resources, the intended use of the wastewater or the capacity to implement certain technologies. Depending on the set-up of the system and the technologies implemented, some indicator may not be relevant for every WWTP.

The validation of the selected indicators

In an attempt to make the set of SDIs as relevant as possible, the indicators, before they were assessed, were discussed with experts familiar with the chosen WWTPs and working at the UMSS Cochabamba. During these sessions, the set of indicators specifically selected for the two WWTPs were examined. The indicators were handed out in form of a list with a short description for each indicator as well as the planned method for its assessment. The result is a set of indicators validated by experts and hence, specifically adjusted to the investigated WWTPs.

The validation of the indicators serves the purpose of avoiding not only the exclusion of relevant but also the inclusion of irrelevant indicators (Bassan et al., 2014). The ladder causes extensive workload while the first may impact the accuracy of the final judgement of the sustainability of the system. Furthermore, some indicators were reformulated to ensure they address the corresponding criterion or the principle, respectively.

3.1.3 Identification of influences within the set of SDIs

The indicators of the same dimension influence each other but there also exist influences across the borders and an indicator within the social dimension may influence an indicator within the environmental dimension (Bassan et al., 2014). Influence diagrams can be used to visualise these interconnections and to emphasize which indicators are influenced and which indicators influence other indicators.

The consideration of all indicators makes the design of influence diagrams very complex and time intense. Due to this, within this work, influence diagrams were formulated for the criteria which are described by the indicators within the set of SDIs.

To respect all influences, each criterion was acknowledged and through literature study and experience the influences were determined. The result is a diagram showing the interconnections between the criteria of the set of SDIs, but it also gives indications on how the indicators may influence each other.

The arrows

The places of conjunction of many arrows belong to criteria that are of great importance for the system and hence, for the set of SDIs. There is a difference, though, between incoming and leaving arrows. The first are arrows indicating that the criterion is influenced by other criteria and the change of those will change that criterion. On the other hand, if many arrows leave from one criterion, that criterion has a high influence on many others. It is important to understand that an arrow leaving from an indicator that apart of this arrow only receives arrows, hence, is influenced by other criteria, may carry the weight of the other arrows.

3.2 Assessment of small WWTPs using a set of indicators

The formulated set of SDIs was used to assess two small WWTPs located in a developing country. The result was used to identify strengths and weaknesses and hereby, to elect the most significant indicators within the set. Moreover, the sustainability of the WWTPs was discussed and compared to limit values if available.

3.2.1 Data collection

Both qualitative and quantitative data were obtained: the indicators described by both qualitative data were obtained by conducting surveys and the indicators demanding quantitative data were obtained by using the available data records. Additionally, for both types of data, previous reports were consulted to complete the set of data, especially for questions not answered within the surveys.

Formulation of questionnaires

Several questionnaires were designed guided by the work of Neuman (2004), each addressing certain indicators and accordingly, containing different questions, respectively for the group affected by those indicators. The questions were formulated clearly to ensure the relevance of the investigated indicator. Instead of entire sentences as answers, the questionnaires yielded to obtain values on the same scale or the same type of answer for each question that could not be answered with yes or no. The reason for this was the lack of expertise in adequately evaluating qualitative data from surveys.

Three types of questionnaires were formulated, two technical and one social orientated. The questions about social aspects were addressed to residents living in the neighbourhoods where the WWTPs are located. For the increased validity of the study, a group of households, in total twenty, that were selected randomly from the associations. To obtain data for the technical indicators, three different groups were approached: the administrative unit of the WWTP, the workers at site which were in both cases the operators and at El Paso also the engineer, as well as the laboratory analysing the wastewater quality of influent and effluent.

The technical questionnaire covered mostly the indicators related to the economic and institutional dimension. However, also questions addressing environmental, social and technical indicators were included. On the other hand, the social questionnaire yielded to find out how the treatment plant is affecting the people living in the area, and therefore, the questions were addressing the social dimension.

Prior to the execution of the surveys, the questionnaires were discussed with experienced engineers to ensure the questions are technically well formulated in order to gather relevant information. Also, students from the Universidad Mayor de San Simón of Cochabamba that already worked with the interviewing of communities, reviewed the questions to ensure they were clear and simple and hence, understandable for also non-educated people.

Analysis of the wastewater quality

The technical questionnaire included questions about the treatment efficiency, i.e. the removal of undesired wastewater constituents and the corresponding limit values are listed in Section 2.4.2. The laboratory at the Universidad Mayor de San Simón of Cochabamba analysed wastewater samples from the influent and the effluent during three different climate seasons: in August, October and February. On every occasion, the samples were taken at the inlet and the outlet. The wastewater constituents that were found to be relevant for a sufficient wastewater treatment at the two investigated WWTPs, the methods to measure their concentration in the wastewater and its number in the catalogue are presented in the following *Table 3.*

Table 3: Wastewater constituents analysed according to the Standard Methods provided by AWWA-ALPHA-WEF (2012).

Constituent	Unit	Method	Number
Oil and grease	mg/L	Extraction	5520 D
TSS	mg SS/L	Gravimetric	2540 D
BOD5	mg O2/L	Ion selective electrochemical	5120 B
COD	mg O2/L	Volumetric oxide reduction	5220 C
Faecal coliforms	UFC/100 mL	Membrane filtration	9222 B
Total N	mg N/L	Several	4500-N
P	mg P/L	Colorimetric	4500-P

3.2.2 Assessment of the sustainability

The set of SDIs was used to assess the sustainability of the two investigated WWTPs in Bolivia. One part was the comparison of limit values or respectively, standards or guideline values to the results of the laboratory analysis of the wastewater quality and the resulting removal efficiency of the treatment chain. Another part was the interpretation of the rest of the data which were more difficult to quantify and often there were no clear benchmarks provided in the literature to compare to. Therefore, the assessment of the sustainability in this report was to a high degree based on discussing the dimensions with its indicators, the comparison to other WWTPs in other countries and to draw a general conclusion from a complicated and wide-wired net of factors indicating a sustainable wastewater treatment system.

Limit and guideline values

To decide whether the obtained data regarding the effluent quality is positive or negative in terms of movement towards sustainable development, limit values were used. These standards were evolved to protect human health and prevent damage to the environment. In Bolivia, the required effluent quality is regulated in the “Reglamento en Materia de Contaminación Hídrica” by the Ley 1333 (Roxendal, 2012) and max. concentrations in the effluent are presented in Table 4. The removal efficiency guideline values were withdrawn from the European Union law and are presented in Table 5.

Table 4: Wastewater constituents and their permitted max. concentration in the effluent. Source: Ley 1333 (1995).

Constituents	**Unit**	**Max. $C_{effluent}$**
Oil and Grease	[mg/L]	10
TSS	[mg/L]	60
COD	[mg O2/L]	250
BOD5	[mg O2/L]	80
Faecal coliforms	[UFC/100mL]	1000
N-tot	[mg N/L]	12
P-tot	[mg P/L]	2

Table 5: Guideline values for the removal efficiency of constituents according the European Union law. Source: EUR-Lex (1991).

Constituent	**Guideline values [%]**
TSS	70-90
COD	75
BOD	90
N-tot	80
P-tot	70-80

To interpret the present salary levels, the minimum wage according to the Bolivian state was considered. In 2018, it was set to 2060 Boivianos per month which at the current exchange rate corresponds to 298 US-$ and is increasing every year (Trading Economics, 2018). Considering a working week of 40 hours, the minimum wage per hour is 1,86 US-$.

3.2.3 Direct comparison of the two WWTPs

At last, the sustainability performance of the two investigated WWTPs was compared. For this purpose, parts of a composite indicator approach introduced by Molinos-Senante et al. (2015) was used.

First, the quantification of the obtained qualitative data was required. This was done by using an eleven-point scale where depending on the question 0 may e.g. indicate the that a certain indicator does not apply while 10 signifies it applies to 100 % and no improvements are needed. In the case of polar questions, 0 equals the negative (away from sustainability) and 10 the positive (towards sustainability) answer.

Second, a normalization of the data was undertaken. Following the procedure provided in the study of Molinos-Senante et al. (2015) indicator by indicator is compared. Here, I is the value of the ith treatment plant of the jth (positive), with $j \in J$, or kth (negative), with $k \in K$, indicator:

$$IN_j = \frac{I_j - I_j^{min}}{I_j^{max} - I_j^{min}} \qquad \text{for positive indicators} \qquad (3)$$

$$IN_k = \frac{I_k^{max} - I_k}{I_k^{max} - I_k^{min}} \qquad \text{for negative indicators} \qquad (4)$$

where IN_{ij} or IN_{ik} is the normalized value of the ith treatment plant, I^{min} and I^{max} are the minimum and maximum value for the jth or kth indicator.

In the given case, not several technologies, but two WWTPs were compared and hence, IN_{ij} and IN_{ik} were assigned with either the value 0 or 1. With this simple method, the WWTPs were compared directly without referring to a reference value. The system receiving a 1 was performing better with regard to that specific sustainable development indicator. For some indicators no data was available and because the monitoring is crucial for sustainability, the lack of data in those cases was considered as the "worst" result when comparing the two WWTPs and was assigned with the value 0. If the two WWTPs were performing equally good, they were both assigned a score of 0,5.

3.3 Identification of significant indicators in developing countries

The revealed strengths and weaknesses of the WWTPs were used to identify some indicators crucial for a sustainable system, i.e. the indicators that were found to be independently relevant for both WWTPs were considered to be of higher significance for a sustainable sanitation system than the other indicators. However, to get an authentic list of significant indicators, experts were consulted to contribute their knowledge and rank the SDIs to determine the overall significance within the total set of SDIs, and respectively, within each dimension.

3.3.1 Ranking the SDIs

To evaluate the most significant indicators within the set of sustainable development indicators, a ranking was conducted. The judgement of experts and local responsible persons ensured that the highest ranked indicators were the most significant ones for WWTPs in developing countries

Method

During an expert meeting, a presentation was given, consisting of a short introduction to the project's objective and a more detailed description of the set of SDIs. Afterward, there was a time saved for discussion and the participants were able to ask question in case of ambiguities. The list of SDIs was handed out to the participants and everyone went through it. The procedure of the ranking was explained: The re, i.e. if a principle contained 8 indicators, ranks from 1 (most significant) to 8 (least significant) were given with respect to the significance within the same principle. The average of the given ranks was calculated to identify the most and least important indicator. At last, the average ranks were divided by the total number of indicators within the dimension to compare them to the indicators of the other dimensions.

A general impression of the perceived importance of the dimensions was obtained after ranking the indicators included in them. For this purpose, the experts were asked to follow the same procedure when weighting the dimensions, i.e. points from 1 to 5 were assigned to each dimension where 5 is the highest that can be received. The points were summed up and the higher the sum the higher the perceived weight *W* of the dimension.

The participating experts were:

- Claudia Cossio – PhD student at UMSS/Chalmers University of Technology; currently working with the assessment of sustainability of wastewater treatment plants in Cochabamba, Bolivia
- Leovigildo Claros Bascofe – Technical Consultant
- Ana Maria Romero – Director of CASA, teacher at department of chemistry
- Alvaro Mercado – Researcher at CASA

- Omar Arce Garcia – Director of the institution for research at the faculty of sciences and technology at UMSS
- Henry Antezana – Professor of chemistry at UMSS; researcher in the field of biotechnology at CASA
- Carlos Acevedo Peña – PhD student at Blekinge Institute of Technology and at the Research Institute-UMSS; Research topic was on Developing Inclusive Innovation Processes and Co-Evolutionary University-Society Approaches in Bolivia.
- Cecilia Saldias – Consultant to evaluate the performance of wastewater treatment plants in Cochabamba; PhD on water resources management (Ghent University).

3.3.2 Normalisation

The normalisation of the average ranking was undertaken by calculating the normalized value as in Section 3.2.3. Since the indicator with the lowest rank was perceived as the most and one with the highest rank the least important indicator, the *Equation (3)* for positive indicators was used.

By normalising, the indicators receive a value between 0 and 1. Only one indicator receives the value 1 and hence, it is recognised as the most significant one by the experts and only one the value 0 and is, respectively, recognised as the least significant indicator. This step was followed first, for all indicators within the set of SDIs and second, for the indicators within each dimension. Significance levels were set at 25 % and a 0,25 - quantile was used to additionally identify other indicators of the set that were ranked very high or low.

In a separate step, the weights *W* for the dimension obtained in the previous step were normalised. Here, by using *Equation (4)* because the higher the rank the more significant is the dimension. The obtained values between 0 and 1, similar as for the indicators, were used to discuss the importance of the single dimensions. Even though one of the five dimensions was inevitably receiving the value 0, all dimensions are crucial for the sustainability of a WWTP.

4 Case study

In this Chapter Four, the chosen WWTPs to be investigated and what the reasons were to have selected these particular two WWTPs are described. By doing this, information about the catchment areas, the type of organization within the WWTP and their set-up are given.

4.1 Choice of wastewater treatment plants to investigate

To make a statement about the existence of problems at more than one site, two WWTPs with a comparable set-up were elected to be investigated. This enables to identify significant indicators with the support of data collected from two different places, but, however, with a similar initial situation. Additionally, reports about other WWTPs in the same department were reviewed to check if the same issues were present.

The area of study within the peri-urban area was found to be most suitable due to the growth of cities in developing countries and hence, it was assumed that in those areas new WWTPs will be implemented in the future. With regard to the purpose of the investigation, to obtain results representative for a wide range of WWTPs in developing countries, WWTPs of a small size (<2000 p.e.) were chosen.

The two investigated WWTPs are located in the peri-urban area of the city Cochabamba, Bolivia (see Figure 23): San Pedro Magisterio, in the east, and El Paso, in the western. Both WWTPs are accessible from the city centre within 45 min by car.

Figure 23: Metropolitan area of Cochabamba with the WWTPs of El Paso (blue circle) and San Pedro Magisterio (orange circle). *Source: Retrieved from Google Earth on 5/07/2018.*

4.2 Set – up of the two WWTPs

As mentioned above, the set-up of the two WWTPs is fairly similar with only small differences in the design and one major abbreviation in form of the lack of a tertiary treatment step at San Pedro Magisterio.

The configuration of the WWTPs is illustrated in Figure 24. The incoming wastewater passes the pre-treatment, which consists of screens and a sedimentation unit, then enters the UASB (Up-flowing-Anaerobic-Sludge-Blanket) as a primary treatment step. The sludge is dewatered on a drying bed and the biogas, in both cases, is burned. After that, during the second treatment step, the wastewater passes a wetland at the WWTP of San Pedro Magisterio and at the WWTP of El Paso an anaerobic filter. At El Paso, there exists also a tertiary treatment consisting of maturation ponds. In both cases, the treated wastewater is discharged into a nearby stream.

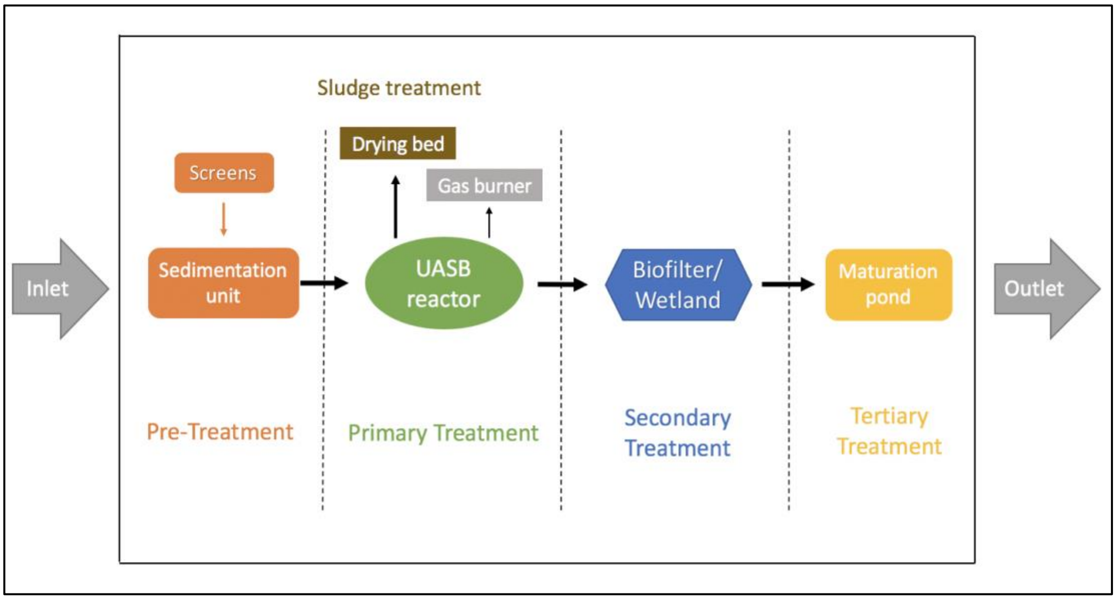


Figure 24: A simple concept of the configuration of the two investigated WWTPs.

4.2.1 El Paso

The WWTP in El Paso is organized by the association for users of potable water and sewage water system. Due to a mistake concerning the geographical location during the planning phase, the WWTP is in operation since 2014, while it was built 9 years before, in 2005. Now, it is located a bit outside of the housing area in the east of El Paso, on land that is owned by the association and accounts to 7102 m^2 of which the WWTP itself is occupying 2947 (see Figure 25). The catchment area compasses 1,32 km^2 but is not densely populated and not all households are connected.

In total, 1200 inhabitants are connected to the drinking water system, but only 534 are connected to the sewage water system, this makes up to 55,5 % of the households. There are three full-time employees in the association: a secretary, an operator and a plumber, all living in El Paso. The operator is living on the WWTP's ground. Additionally, an engineer, a legal advisor and a consultant are non-permanent employed. As part of their philosophy, informative events are organized to involve the community.

Figure 25: The WWTP of El Paso (framed in light blue) and the close-by stream "Río Mal Pasomayu" (dark blue). *Source: Retrieved from Google Earth on 5/07/2018.*

The configuration is described in more detailed in Figure 26. Detailed pictures of the technologies can be found in Appendix A.

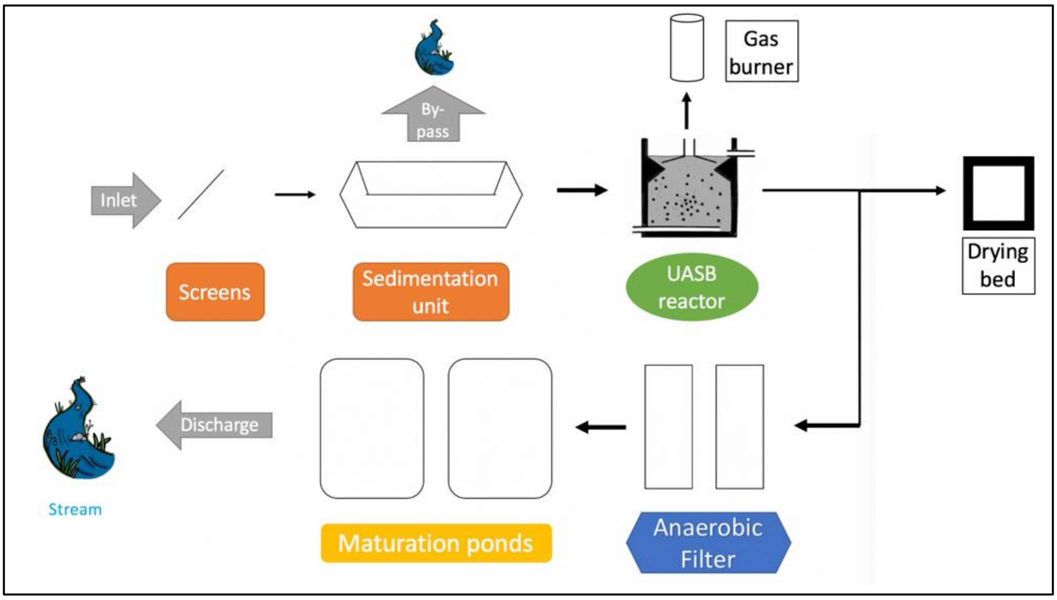


Figure 26: More detailed sketch of the configuration of the WWTP El Paso.

The primary treatment consists of a screen and a sedimentation unit inform of two parallel lines, of which one is in operation, while the other one is detached from the system to be cleaned (see Figure 27 left). Furthermore, this unit has a bypass that is used to discharge the wastewater, in times of heavy rains to protect the other treatment units, to the stream without further treatment. The UASB, with a circular design, is part of the primary treatment. The produced gas is burned, and the excess sludge is removed and treated on the drying bed. Leaving the UASB, the wastewater enters one of the two anaerobic filter basins as a secondary treatment (see Figure 27 right) and flows horizontally through it. These basins were designed and constructed with a lid that was removed later. Then, the secondary effluent reaches the maturation pond as part of the tertiary treatment step (see Figure 27 right), before the treated wastewater is discharged to a small stream.

Figure 27: Treatment units at the WWTP of El Paso. Left: Primary treatment unit with screens, sedimentation channels and bypass. In the background the circular basin of the UASB reactor. Right: Secondary treatment unit consisting of two anaerobic filters (right), the outlet and the maturation pond as a tertiary treatment step (left). *Author's own copyright (Photos were taken in February 2018).*

4.2.2 San Pedro Magisterio

Located close to the Cerro San Pedro in the District 2 of the municipality of Sacaba, the WWTP of the neighbourhood San Pedro Magisterio, also called *Friuli,* is the result of a project of the *Fundación Abril* of Cochabamba and the *Cooperativa de agua* of San Pedro Magisterio, while the land is owned by the *OTB* (Organisación Teretoriál del Base). The catchment area accounts to 139 221 m^2 and the WWTP occupies 1493 of a total available area of 1 947 m^2 southwest of a dense housing area (see Figure 28).

The WWTP is operating since April 2015 and the water of 1500 inhabitants of 2680 is treated and therefore, 56 % of the households connected to the WWTP. The design flow, however, only considers 970 connections and hence, 30 % of the capacity is not used yet. According to the project proposal, an average incoming wastewater flow of 91 L/d*pers was assumed.

There are five full-time employees: a secretary, an operator, an administrator, an accountant and a plumber. As in El Paso, also in San Pedro Magisterio events with the objective to inform the users are organized at least once per year.

Figure 28: The WWTP of San Pedro Magisterio and its catchment area (framed in orange). *Source: Retrieved from Google Earth on 5/07/2018.*

The configuration is described in more detailed in Figure 29. Detailed pictures of the technologies and corresponding design drawings can be found in Appendix A.

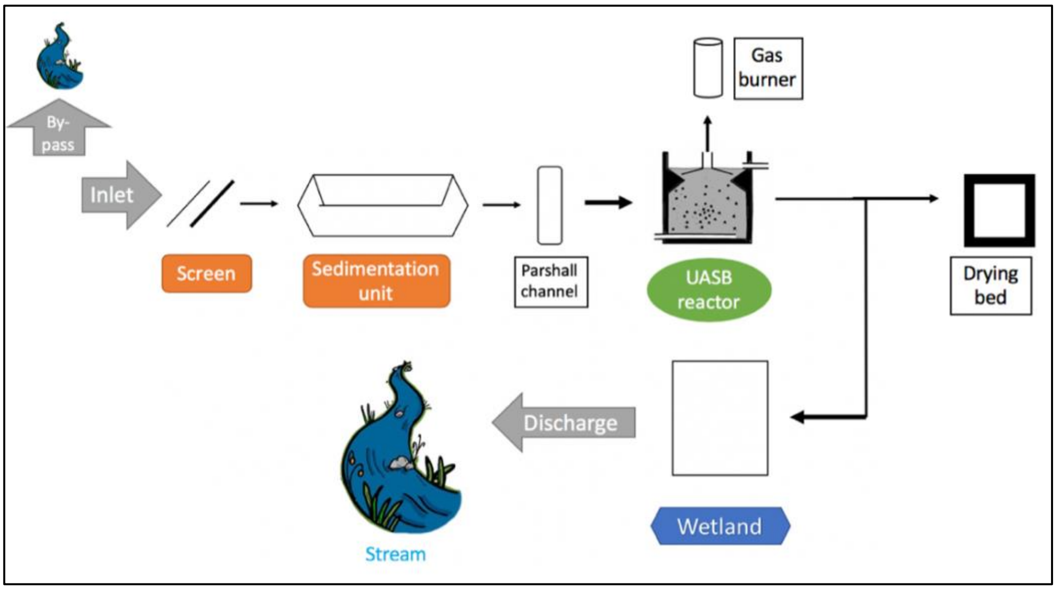


Figure 29: More detailed sketch of the configuration of the WWTP of San Pedro Magisterio.

There are small differences between the configurations of the two investigated WWTPs. In San Pedro Magisterio, the bypass is located before the wastewater passes through the two screens in series, and then, enters the sedimentation channel. Additionally, there is a Parshall channel implemented to reduce the velocity at the end of the primary treatment unit to protect the sludge blanket in the UASB reactor (see Figure 30 left). The UASB, with a rectangular design, is part of the primary treatment step (see Figure 30 right). The produced gas is burned, and the excess sludge is removed and treated on the drying bed (see Figure 31 top). Another aberration is the second unit that consists of a Horizontal Subsurface Flow Constructed Wetland (see Figure 31 bottom). After this step, the treated wastewater is then, without any tertiary treatment, discharged to the Río Rocha, a stream that passes downstream the centre of Cochabamba.

Figure 30: Primary treatment unit (left) with two screens in series, the sedimentation unit and the Parshall channel, and the UASB reactor (right) at the WWTP of San Pedro Magisterio. *Authors own copyright (Photos were taken in February 2018).*

Figure 31: Drying bed, connected to the UASB reactor (on top) and planted wetland with horizontal flow (on bottom) at San Pedro Magisterio. *Authors own copyright (Photo was taken in February 2018.*

5 Results

By following the methodology provided in Chapter Three, the results given in this Chapter Five were obtained. Two sets of SDIs s are presented in this chapter: the first is a collection of all indicators considered relevant for the sustainable development of wastewater treatment systems in developing countries, contains 64 indicators and is presented in Section 5.1, the second is a set specially formulated for the two investigated WWTPs and hence, is a slightly shorter list with some indicators eliminated from the first list according to the present conditions at the WWTPs in Cochabamba and is presented in Section 5.2. The ladder additionally contains the actual assessment of the sustainability of the two WWTPs and the comparison of the two WWTPs. The last part of the result section is the identification of significant indicators (Section 5.3). The tables relevant for the Sections 5.2 and 5.3 are provided in Appendix C, D, and E.

5.1 The set of sustainable development indicators

Besides the main dimensions (here also called aspects) of environmental, social and economic aspects, the technical aspect was considered a relevant dimension for the assessment of the WWTP's configuration, and moreover, an institutional dimension was added (Andersson et al., 2016). In the following, the principles within the dimensions, their criteria and the describing indicators are shown in *Table 6* to *10.*

To use the set of SDIs to assess the sustainability of WWTPs, indicators were taken from various studies with different research objectives, but a major contribution was the study by Singhirunnusorn and Stenstrom (2009) that identified indicators and criteria for appropriate wastewater treatment systems in a developing country in Asia, in Thailand. This approach resembles to a great extent what was intended with this study and therefore, the indicators were assumed to be suiting the purpose of the assessment of WWTPs in a developing country.

Indicators within the economic dimension (*Table 6)*

The indicators within the economic dimension reveal all costs involved in the construction as well as in the management, i.e. costs due to operation and maintenance of a WWTP (Molinos-Senante et al., 2015). Therefore, the affordability of the WWTP is the key principle within this dimension.

In the initial phase of implementing a WWTP, certain investments must be taken to enable its construction (Molinos-Senante et al., 2015). The *Construction cost* increase with an increasing level of treatment required and decrease proportionally, with respect to the population equivalent, for higher capacities (Tsagarakis et al., 2002). The *Land cost* can be determined by the price it would have been worth if used for another purpose. In developing countries, the *Cost subsidy from the government* determines the system and the technologies that will be implemented as well as the number of personnel to be employed (Singhirunnusorn and Stenstrom, 2009).

The O&M costs are related to the management of the WWTP and cover the cost emerging within the treatment (Palmer and Mattsson, 1994) and are essential for the assessment of the feasibility of the facility (Hernandez-Sancho et al., 2011). The *Operational cost* includes the money required for energy, chemicals and other materials (Cornel and Krause, 2008; Katukiza et al., 2010). Moreover, as pointed out by Tsagarakis et al. (2002), it also covers the cost required for the sludge management. As noted by Fraas and Munley (1984), an increase in cost can be observed when the amount of wastewater treated increases as well as when the contamination level of the influent increases. It also depends on the level of effluent quality that must be achieved and if the sludge is going to be reused and therefore, must be treated accordingly. U.S. Environmental Protection Agency (2013) identified the energy consumption of a WWTP is one of the main contributors to the total O&M costs. Interestingly, in relation to the population equivalent, when assuming the same configuration, smaller WWTPs have a higher energy demand (Tsagarakis et al., 2002). The chemicals used depend on the treatment processes involved. According to Tchobanoglous et al. (2003), most commonly, chlorine gas (Cl2), chlorine compounds and ozone (O3) are used for the disinfection process step, and alum and lime for the coagulation. The proper usage of the chemicals can reduce the amount consumed and hence, reduce the money required for the purchase. A bigger WWTP needs fewer workers per cubic meter treated water (Tsagarakis et al.,2002). Additionally, the automatization of process steps leads to fewer employees and as a result, lower *Administration cost*. On the other hand, if many mechanical systems are involved, more staff is required than for natural systems. The exists a correlation between the degree of educated personnel and the number of employees, since problems can be solved faster by trained staff, and knowing the processes and the systems helps to work more efficiently. The cost for the personnel depends highly on the grade of education of the employees (scientific, technical, unskilled). The *Maintenance cost* covers the money spent within the facility to prevent failures of processes and systems, i.e. for constructional repairs, the repairing of mechanical and electrical systems as well as for replacements of system components. While the maintenance costs cover the cost for yearly repairs, there should be a *Capacity for re-investment* to potentially re-invest in the system but also scope with unexpected cost as failures might occur within the system (Personal communication with Cossio, November 2017).

Table 6: The economic aspect, its principles, criteria and indicators.

Aspects	**Principles**	**Criteria**	**Indicators**	**Source for indicators**
Economic	Affordability	Initial cost	Construction cost	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000); Molinos-Senante et al. (2014); Muga and Mihelcic (2008)
			Land cost	Singhirunnusorn and Stenstrom (2009)
			Cost subsidy from government	Singhirunnusorn and Stenstrom (2009)
		Operation and Maintenance cost	Operational cost	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000); Molinos-Senante et al. (2014); Muga and Mihelcic (2008
			Maintenance cost	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000); Molinos-Senante et al. (2014); Muga and Mihelcic (2008)
			Administration cost	Singhirunnusorn and Stenstrom (2009)
			Budget for unexpected repairs	Singhirunnusorn and Stenstrom (2009)
		Capacity for re-investment	Money available to reinvest	Singhirunnusorn and Stenstrom (2009)

Indicators within the technical dimension (*Table 7)*

As wastewater treatment plants are technical systems, the efficiency, the complexity and the continuity are crucial principles for its sustainability (Singhirunnusorn and Stenstrom, 2009). The efficiency results out of the capacity of the WWTP which is described by the relation between the *Amount of wastewater received and the design flow* and the removal of undesired constituents, as the *Removal of oil and greases, TSS, COD, BOD, Faecal coliforms, Total nitrogen and Phosphorus* during the wastewater treatment. These two principles were found to be significant concerning the sustainability of WWTPs (Singhirunnusorn and Stenstrom, 2009). The complexity of both initial phase and O&M can impact the costs and also the efficiency and continuity of the WWTP. The lower the *Complexity of the initial phase* the easier the construction, the installation and the starting of the system, the lower the *Time required for initial phase*, and hence, the cheaper the investment cost. In developing countries, the implementation of advanced technologies as well as the missing *Accessibility provided through infrastructure* can lead to the malfunctioning of the system due to the *Complexity of the O&M* (Baccarini, 1996) accompanied by the lack of money for *skilled staff* and hence, the inadequate execution of O&M (Singhirunnusorn and Stenstrom, 2009). Accordingly, the indicator *Requirement of training for staff* is directly connected to the solution for the previous mentioned problems. The continuity ensures the time reliability of the WWTP's performance in terms of meeting the discharge requirements for a percentage of time (Tchobanoglous et al., 2003; Oliveira and Von Sperling, 2008) and the provision of a buffer capacity which corresponds to available unused capacity (Sadr et al., 2014) due to an expanding population and the need to access for more people to improved sanitation, and hence, WWTPs will face higher flows of wastewater (Verbyla et al, 2013). The *Time of reliable operation* is characterized by sufficient treatment that is not at-risk due to failures of the system (Molinos-Senante et al., 2015).

Table 7: The technical aspect, its principles, criteria and indicators.

Aspects	**Principles**	**Criteria**	**Indicators**	**Source for indicators**
Technical	Efficiency	Capacity of plant	Amount of wastewater received and design flow	Lundin et al. (1999)
		Removal of constituents	Oil and greases	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Muga and Mihelcic (2008)
			Total suspended solids (TSS) in the pre-treatment	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Muga and Mihelcic (2008)
			Total suspended solids (TSS)	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Muga and Mihelcic (2008)

Table 7 (continuous): The technical aspect, its principles, criteria and indicators

Technical	Efficiency	Removal of constituents	Chemical oxygen demand (COD)	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014)
			Biological oxygen demand (BOD)	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Lundin et al. (1999); Muga and Mihelcic (2008)
			Faecal coliforms	Singhirunnusorn and Stenstrom (2009); Muga and Mihelcic (2008)
			Total nitrogen	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Lundin et al. (1999); Muga and Mihelcic (2008
			Phosphorus	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Lundin et al. (1999); Muga and Mihelcic (2008

Table 7 (continuous): The technical aspect, its principles, criteria and indicators.

Technical	Complexity	Initial phase	Complexity of initial phase	Singhirunnusorn and Stenstrom (2009); Baccarini (1996)
			Accessibility provided through infrastructure for O&M	Singhirunnusorn and Stenstrom (2009)
			Time required for initial phase	Singhirunnusorn and Stenstrom (2009)
		Operation and maintenance	Complexity of O&M	Singhirunnusorn and Stenstrom (2009)
			Requirement of skilled staff	Singhirunnusorn and Stenstrom (2009); Muga and Mihelcic (2008); Bassan et al. (2014)
			Requirement of training for staff	Singhirunnusorn and Stenstrom (2009)
	Continuity	Life expactancy	Time of reliable operation	Singhirunnusorn and Stenstrom (2009)
		Buffer capacity	Available unused capacity	Singhirunnusorn and Stenstrom (2009)

Indicators within the environmental dimension (*Table 8*)

In terms of environmental protection, the system's performance in resource consumption and recovery, its GHG emissions and the achieved effluent quality, as well as the land requirement, are considered (Molinos-Senante, 2014).

The resources contained in the wastewater can be valuable and their recovery decreases their extraction or the extraction of other resources from the environment, and therefore, the strain on the environment. As stated by Scholz et al. (2013), phosphorus is considered a valuable resource within the agricultural sector and is crucial for today's and future food supply. The *Recovery of phosphorus and nitrogen* will gain importance within the future due to the depletion of the non-renewable resource. During the treatment of wastewater, biogas, a gas composed of methane and other gases, may be produced in case of the anaerobic digestion of sludge, a method that was found to be often used in WWTPs (Osorio and Torres, 2009). By the *Recovery of biogas*, energy can be obtained and by that, the consumption of non-renewable energy sources can be reduced. An inevitable by-product of the wastewater treatment is the sludge which contains pathogens, nutrients and organics that were removed from the wastewater and chemicals that were used during the treatment process (Babatunde and Zhao, 2006). The amount of produced sludge depends on the size of the WWTP but often the costs for disposal are another main contributor to the operational costs. *Sludge reuse* can happen during the treatment process to improve the performance of the WWTP, it can be treated to remove pathogens and chemicals and be used for agricultural purposes and the during the processing of the sludge emitted methane can be used to produce energy. Miller (2006) suggests that the reuse of wastewater must be considered to cover the future supply by reducing the consumption of fresh water, a limited resource. Present studies as the one of Garcia and Pargament (2015) confirm that the wastewater can be used for irrigational purposes and imply that with new technologies a sufficient quality can be achieved to even reuse it as supply for urban and potable water. With respect to this, the potential for *water reuse*, i.e. the fulfilment of certain regulations, depends on what it will be used for.

In water-scarce regions, the *Amount of fresh water consumed during the treatment process* should be as low as possible to ensure water security and protection of the environment (Risch et al., 2014).

There exist many chemical unit processes for the treatment of wastewater, and Tchobanoglous et al. (2003) found some of them to be commonly implemented. The use of chemicals can enhance the performance of the treatment and have a wide range of application as for e.g. coagulation, disinfection, neutralization or oxidation. The kind and the *Amount of chemicals consumed during the treatment process* depends on the purpose of the addition and on the influent quality. However, the negative aspect is that constituents are added to the wastewater and may release disinfection by-products (DBPs) to the environment (Asano et al., 2007) or may influence subsequent treatment steps. Furthermore, the costs for chemicals can be very expensive. Therefore, the amount of chemicals should be as low as possible. In a wastewater WWTP, the use of materials is common for e.g. the change of filter media. To reduce the costs and protect resources, the *amount of materials consumed during the treatment process* should be as low as necessary, i.e. without decreasing the performance of the WWTP. The energy consumption covers the *Electricity consumed during the treatment process* and has an impact on the environment (Sadr et al., 2014) as explained in the next paragraph. A major impact on the consumption have pumps (U.S. Environmental Protection Agency, 2013) and processes as e.g. the aeration (Jetten et al., 1997). The amount of energy produced by e.g. the recovery of biogas would compensate a part of the energy consumed (U.S. Environmental Protection Agency, 2013).

The emissions of certain gases are considered to contribute to global warming and according to the Kyoto-Protocol, they must be reduced worldwide (Shine et al., 2005). Campos et al. (2016) identified the following greenhouse gases (GHG) to be emitted during the process of wastewater treatment: methane CH_4 during anaerobic digestion, nitrous oxide N_2O and carbon dioxide CO_2. The global warming potential (GWP) is expressed as CO_2-equivalent and e.g. methane has a GWP of 25 CO_2-equivalents (Daelman et al., 2012) and accordingly, it contributes much more to the global warming than CO_2 itself. Next to the direct emission of those gases during the treatment, greenhouse gases are indirectly emitted by consuming electricity and materials and during transportation outside the boundaries of the WWTP (Bani Shahabadi et al., 2010). Therefore, the *GHG emitted* is closely related to the energy consumption of the WWTP and is expressed as the equivalent of kg CO_2 emitted to the atmosphere. Therefore, energy efficient treatment not only reduces the cost of operation but also lowers impact on the environment.

The controlled release of contaminants ensures a sufficient quality of the effluent which is crucial to protect the environment and human health (Andersson et al., 2016). The wastewater constituents that must be removed are the following, according to Tchobanoglous et al. (2003): *Total suspended solids (TSS)* [mg SS/L] which can cause sludge deposits and anaerobic condition when released to the recipient water body, biodegradable organics (*BOD*, *COD*) [mg O_2/L] which is the demanded oxygen for biological stabilization and therefore, the presence in the water can lead to anaerobic conditions in the environment, and pathogens (*faecal coliforms*) [UFC/100 mL] which can transmit diseases. The release of nutrients, like *Nitrogen and hosphorus*, can pose the risk of eutrophication and lead to severe changes in aquatic and terrestrial ecosystems (Smith et al.,1999; Tchobanoglous et al., 2003). In reason of this, the release to the environment must be controlled. *Cadmium, mercury, copper and lead* are highly toxic heavy metals and their release must be prevented to protect human health and the environment (Tchounwou et al., 2012).

The *Total area required* for the WWTP has an economic and a recreational value because it could be used for e.g. agricultural land or as green space. The impact on society is reduced by increasing the *Area of the buffer zone*, i.e. the area between the WWTP and the settlements. These two indicators are describing the principle of the land requirement of the WWTP.

Table 8: The environmental aspect, its principles, criteria and indicators.

Aspects	**Principles**	**Criteria**	**Indicators**	**Source for indicators**
Environmental	Resources	Recovery	Phosphorus and nitrogen	Hellström et al. (2000); Lundin et al. (1999)
			Biogas recovered	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000)
			Sludge reuse	Molinos-Senante et al. (2014); Lundin et al. (1999)
			Water reuse	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014)
		Water consumption	Amount of fresh water consumed during treatment process	Hellström et al. (2000)
		Use of chemicals	Amount of chemicals consumed during treatment process	Hellström et al. (2000)
		Use of materials	Amount of materials consumed during treatment process	Hellström et al. (2000)
		Energy consumption	Electricity consumed during treatment process	Hellström et al. (2000); Muga and Mihelcic (2008); Bradley et al. (2002)

Table 8 (continuous): The environmental aspect, its principles, criteria and indicators.

Environmental	Emissions	Carbon footprint	GHG emitted	Hellström et al. (2000)
	Release of contaminants	Effluent quality	Total suspended solids (TSS)	Bradley et al. (2002); Metcalf and Eddy (2003)
			Chemical oxygen demand (COD)	Singhirunnusorn and Stenstrom (2009); Lundin et al. (1999); Bradley et al. (2002)
			Biological oxygen demand (BOD)	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000)
			Faecal coliforms	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000)
		Risk of eutrophication	Total nitrogen	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000)
			Phosphorus	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000)
		Heavy metals	Cd, Hg, Cu, Pb in effluent	Hellström et al. (2000)
	Land requirement	Size	Total area required	Singhirunnusorn and Stenstrom (2009); Hellström et al. (2000); Molinos-Senante et al. (2014)
			Area of buffer zone (noise, odour)	Singhirunnusorn and Stenstrom (2009)

Indicators within the social dimension (*Table 9*)

In sustainable development, the implementation of a social dimension covers the affection of the society by the wastewater treatment plant (Hellström et al., 2000).

The awareness and satisfaction of the people are important because insufficiently treated wastewater has a *Health impact* and an *Environmental impact* that need to be understood. A functioning wastewater system starts at the household level and society's *Satisfaction with the sewage system* leads to a higher willingness to participate. Access should be provided to all households within the catchment area of the WWTP to improve the living standards. Moreover, high *Sewage coverage* increases the protection of health and the environment.

The acceptance of the public is determined by the impact of *noise* and *odour* emissions, as found by Molinos-Senante (2015), but also by the *participation in O&M* which is especially important for decentralised systems (Bdour, 2007). Besides, the *Visual impact* of the WWTP can cause disapproval. If the users don't accept the system, there is a lack of *Willingness to pay a fair tariff for collection and treatment* of the wastewater.

Indicators within the institutional dimension (*Table 10*)

The experience regarding WWTPs in developing countries of Claudia Cossio was used to include several indicators within the institutional dimension after personal communication in November 2017. The institutional aspects were developed, and the following principles are represented: The *Level of institutional capacity*, the *Record of data*, the *Level of interaction with users*, the *Level of satisfaction with the working conditions*, and the *Level of autonomy*. The functionality of the treatment plant must be ensured by enough *Technical and administrative human resources* as well as *Available supplies and equipment*. Additionally, the data regarding the quantity of incoming water, the quality of influent and effluent must be recorded accurately to maintain the WWTP's performance, and infrastructure plans should be accessible to facilitate O&M. To provide social sustainability, the involvement of the society through annual meetings and/or an annual report should be provided by the institution. Moreover, an adequate salary and the safety of the WWTP's workers must be provided to ensure their satisfaction and hence, their caring about the work.

Table 9: The social aspect, its principles, criteria and indicators.

Aspects	**Principles**	**Criteria**	**Indicators**	**Source for indicators**
Social	Awareness and satisfaction	Awareness	Health impact	Hellström et al. (2000); Bradley et al. (2002)
			Environmental impact	Singhirunnusorn and Stenstrom (2009)
		Level of satisfaction	Satisfaction with the sewage system	Singhirunnusorn and Stenstrom (2009)
	Access	Sewage system	% of sewage coverage	Lundin et al. (1999)
	Acceptance	Public	Willingness to pay a fair tariff for collection and treatment	Singhirunnusorn and Stenstrom (2009)
			Participation in O&M	Singhirunnusorn and Stenstrom (2009)
			Odour	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Muga and Mihelcic (2008); Bradley et al. (2002)
			Noise	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Muga and Mihelcic (2008); Bradley et al. (2002)
			Visual impact	Singhirunnusorn and Stenstrom (2009); Molinos-Senante et al. (2014); Bradley et al. (2002)

Table 10: The institutional aspect, its principles, criteria and indicators.

Aspects	**Principles**	**Criteria**	**Indicators**	**Source for indicators**
Institutional	Institutional aspects	Level of institutional capacity	Available technical human resources	Claudia Cossio, November 2017; Bassan et al. (2014)
			Available administrative human resources	Claudia Cossio, November 2017; Bassan et al. (2014)
			Available supplies and equipment	Claudia Cossio, November 2017
		Records of data	Record of flows	Claudia Cossio, November 2017
			Record of analysis of the quality of wastewater	Claudia Cossio, November 2017
			Plans of the infrastructure	Claudia Cossio, November 2017
		Level of interaction with users	Number of communication events with users	Claudia Cossio, November 2017
			Number of annual socialized reports with users	Claudia Cossio, November 2017
		Level of satisfaction with working conditions	Level of salary	Claudia Cossio, November 2017
			Safety conditions (clothes, hygiene and health)	Claudia Cossio, November 2017
		Level of autonomy	Property of land and fixed activities	Claudia Cossio, November 2017
			Auto-sustainable financing (own means)	Claudia Cossiom November 2017; Singhirunnusorn and Stenstrom (2009); Bassan et al. (2014)

5.1.1 Identification of influences within the set of SDIs

An overview of the influences between the criteria is provided in Figure 32. The diagram helps to better understand the interconnections within the set of SDIs. Even though, here, the criteria were considered, their describing indicators and hence, their influences were indirectly included.

As can been seen, the criteria of the five dimensions do not only influence criteria of other dimensions but also the indicators within their own dimension, as e.g. the "Removal efficiency" of wastewater constituency may influence directly the "Complexity of O&M" due to more sophisticated technologies or the negative impact of increased Energy consumption on the environment is directly interconnected with the "Carbon footprint" of the WWTP. Other influences indicated in the diagram are potential, but their activation is not certain. Rather, they depend on the kind of changes occurring within the influencing criterion. The "Complexity of the initial phase can have an influence on the "Complexity of O&M" in the case of poor construction leading to the lack of accessibility provided through infrastructure.

As can been retrieved from the Figure 32, the "Removal efficiency" as technical, the "O&M costs" as economic, and the "Acceptance ", as social criterion are influencing or are influenced by many other criteria and hence, are of high importance for the set of SDIs. Especially, a change within the criterion of the "Removal efficiency" will have an impact on many other criteria as the "Effluent quality", the "Risk of Eutrophication", and the "Complexity of O&M". Contrary, the "Acceptance" is influenced by various criteria that are not influencing and are not influenced by another criterion. This means, that the change of the awareness through the change of many of those single criteria will lead to a strong influence of the "Acceptance" on another criterion. It is the only criterion within the social dimension serving as a conjunction point. Only few arrows can be found when looking at the criteria within the environmental dimension. The criteria within the institutional dimension seem to have the lowest impact; however, all five criteria are influencing directly or indirectly the three criteria mentioned above as the most influencing ones.

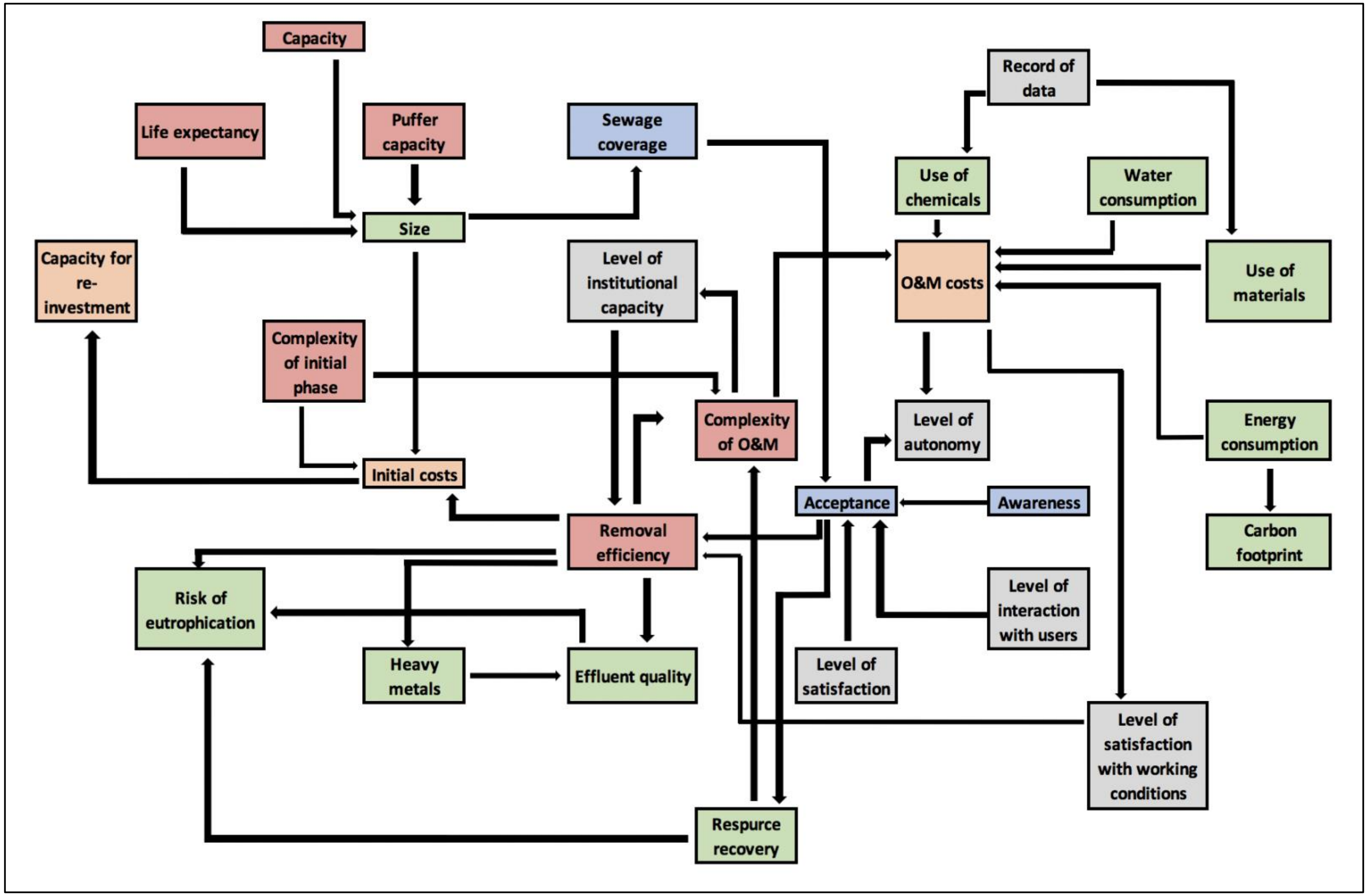


Figure 32: Influence diagram of the criteria included in the generated set of SDIs.

5.2 The assessment of two WWTPs in Bolivia

From the set presented in the previous section, indicators were selected, and the final set of SDIs was formulated and is presented in the first part of this section. Followed by the actual assessment using this set and a direct comparison of the two WWTPs.

5.2.1 The final set of indicators

All indicators listed in Section 5.1 are relevant for sustainable wastewater treatment systems; however, depending on the system's configuration, local conditions and the present regulations, not all indicators are significant for every treatment system. For example, the criterion "Resource Recovery" includes the indicators *Phosphorus recovery, Biogas recovery, Sludge reuse and Water reuse*. If there is no anaerobic digestion, the production of biogas is low and might be not feasible as an energy source. Additionally, the availability of data is important to avoid the acquisition of inaccurate data which may result in a false notion about the sustainability of the system.

The indicator *participation in O&M* was excluded from the list since the two investigated systems are semi-decentralised and the O&M must be executed by trained staff. After discussing the set of indicators with experts as Claudia Cossio and Sebastien Rauch who both are actively involved in the assessment of WWTPs in Cochabamba, two indicators were found to be unessential during the first session: the *GHG emitted*, and the *Release of heavy metals*. The first was eliminated for the complexity of capturing of all greenhouse gases emitted within a system since it demands special data records and is a work-intensive procedure that exceeds the scope of this work. There are no industries located near the treatment plants and according to local experts, the incoming water to the treatment plant is no contaminated with heavy metals and thus, the released number of toxics is not considered. Moreover, in reason of difficulties in the obtainment of relevant data and its quantification, the indicator *Time of reliable operation* was excluded after getting a first impression of the data available at site and at the university in Cochabamba.

The final set of indicators was used to investigate the two WWTPs and assess their sustainability performance and contains 60 indicators what makes it very extensive. However, due to the awareness that data acquisition is often difficult in developing countries and the elimination of indicators may lead to a thin data set, many indicators that could have been ignored were included to prevent the false interpretation of the collected data.

5.2.2 Sustainability assessment

To get an impression of the dimensions, hence, the expenses, the performance, the social acceptance, the impact on the environment and the institutional organisation of the WWTPs, questions addressing the corresponding indicators were formulated and grouped in questions asked to the administrational unit of the WWTP, the workers at site as well as the laboratory at the UMSS, and to a random sample of residents. The three questionnaires can be found in Appendix B and the *Table 11 to 15* in Appendix C provide an overview which questions address which indicator. Moreover, the units in which the answers were given as well as the answers for both WWTPs are presented.

The economic dimension (*Table 11* in Appendix C)

For the initial construction of the treatment plant of El Paso, 86 862 US-$ had been invested. Due to mal-designing inform of miscalculation of the inclination of the terrain, the entire WWTP needed to be reconstructed and an additional 202 678 US-$ were required. The first amount, 43 % of the total cost, was subsidised by the government while the costs for the changes were carried by the association (see Figure 33). The ground the treatment plant is built on was provided free of charge from the owner but is estimated to have a monetary value of 46 000 US-$.

It was stated that in reason of the biological treatment units no energy is consumed during the treatment process. The cost of chemicals was unknown and considered as neglectable by the engineer due to the small amount in which calcium oxide is added during the treatment process. Some materials as sand, gravel and paint colour are consumed during the year; however, there was no information available regarding the amount consumed or the yearly cost of those. As a result, the recorded operational cost per month is 0 US-$. The salaries of the WWTP's three employees account for 1 072 US-$ per month and are, as administration costs, part of the total costs of O&M (see Figure 34). There is no percentage paid directly by the association for the insurance or pensions of the employees. Because it was difficult to distinguish between the costs of operation and the ones of maintenance per month, a question addressing the entire cost was given to the administrative unit. To operate and maintain the WWTP, 965 US-$ are spent every month. In case of emergency cases, as e.g. the failure of a treatment technology due to break-down, there is no budget available to cover unexpected costs. Also, there is no budget to re-invest into the WWTP in order to expand its capacity or improve the treatment efficiency.

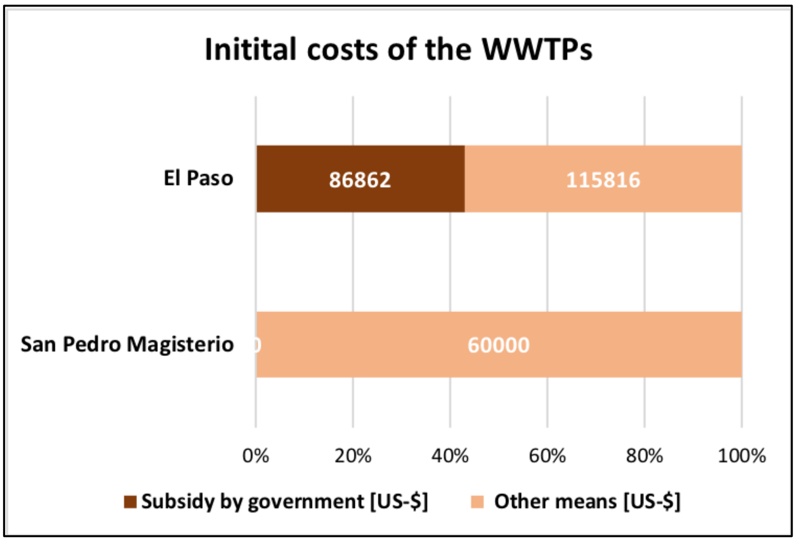


Figure 33: The initial costs and the amount subsidised by the government.

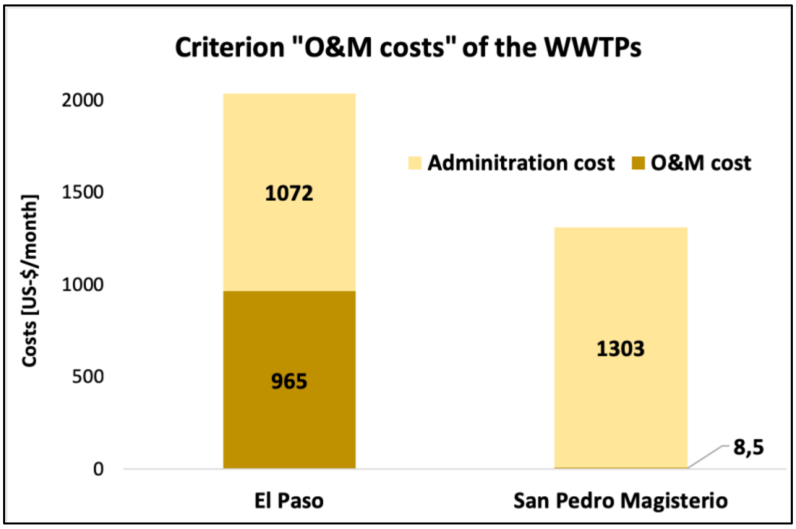


Figure 34: The monthly costs of operation and maintenance at both treatment plants.

For the initial construction of the treatment plant of San Pedro Magisterio, 60 000 US-$ had been invested (see Figure 33). Contrary to El Paso, there was no support from the government, but the money required was to 100 % donated by the NGO, the Foundation “Abril” and the centre of international volunteers (CEVI). To lower the initial costs, the public was motivated to actively help in the construction process. Furthermore, money was saved by the provision of the land through the territorial organization base (OTB) which are groups in neighbourhoods formed to improve their public services.

Due to the location of the WWTP in a depression, the pipes run downward, and no pumps were installed and hence, no energy is consumed for the transportation of the wastewater. Additionally, the anaerobic technologies allow an energy- and chemical-free treatment. Some materials as sand, gravel, painting colour and wire mesh are bought during the year and cost approximately 8,5 US-$ per month and because it is the only cost recorded, the operational cost per month is 8,5 US-$. There is no information available for the maintenance cost. The five permanent employees at the WWTP are paid in total 1 303 US-$ per month and is equal to the administration cost because no money is paid to insurance companies or for a pension of the employees. The total O&M costs are presented in Figure 34. Neither is money available to reinvest nor were there information regarding the budget for unexpected costs.

The technical dimension (*Table 12* in Appendix C)

In El Paso, 2,8 l (242 m^3) wastewater produced by 534 households enter the WWTP per second (day) which is only 28 % of the design flow. Hence, another 7,2 L/s could be treated which equals the connection of 1373 more households to the WWTP.

The efficiency of the WWTP is characterized by the removal of constituents of the wastewater and is presented in Figure 35. To make the following treatment technologies work properly, oil and grease, as well as TSS, must be removed during the pre-treatment. At El Paso, no sampling takes place after the pre-treatment and as a consequence, the removal through screens and sedimentation channel is unknown. However, samples were taken after the primary treatment (UASB) and a removal of 46 % of TSS was determined. For the other constituents, the removal efficiency was calculated using the concentration in in- and effluent. Greases and oil are reduced by 41 % before the wastewater is released to the environment. The total removal of TSS is 80 % and therefore, fulfils the requirements of 70 to 90 % according to the European Union law (compare to *Table 5* in Section 3.2.2). The percentage of removal achieved for COD are with 69 % below recommended 75 %, but especially 20 % removal of BOD_5 is far below the guideline value of 90 %. The removal of faecal coliforms is with 90 % still insufficient. Depending on the sensitivity of the recipient water as well as on the intended reuse of the wastewater, the limit values for the concentrations of nutrients varies. There is no clear information about the reuse and the sensitivity of the recipient water is unknown. Hence, the recommended percentage of removal of 80 given by the European Union law is used to assess the performance, but even if considering the Swedish EPA standards of 50 % for nitrogen (high protection level) and 90 % for phosphorus (normal protection level) (Roth et al., 2017), the achieved removal efficiencies are with 5,25 % very low for nitrogen and with -11,6 % even negative for phosphorus.

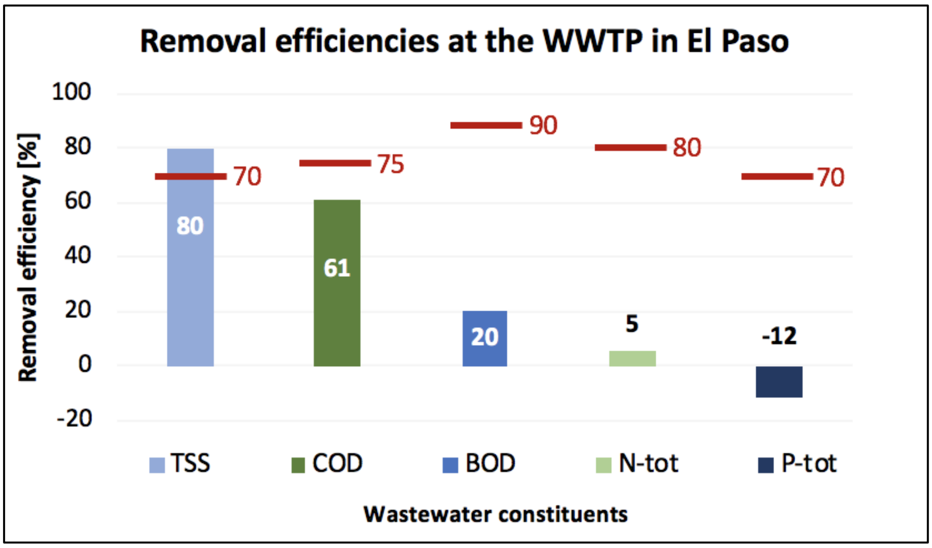


Figure 35: The removal efficiencies in [%] of the wastewater constituents through the entire treatment at the WWTP in El Paso (in columns) and the guideline values according to the European Union law from 1991 (red lines).

Regarding the complexity of the initial phase no information was available, but the time from the beginning of the planning phase to the initiation of the WWTP took almost 9 years which is a major cause for the high resulting construction cost and indicates a certain complexity of this phase or a lack of qualified engineers designing the WWTP. The accessibility provided through infrastructure for the execution of O&M was judged as satisfying by the operator and the administrator, but as poor by the engineer due to the problems evolving from a poor design of the UASB reactor that leads to complications during O&M because it is extremely hard accessible. The operator is supporting this by indirectly referring to the UASB reactor as the most complicated treatment unit to operate. The engineer is visiting the WWTP regularly, but a permanently employed engineer is missing in the institution. Furthermore, the question regarding the potential need for training was affirmed and it was explained that an increased qualification of the staff working at the WWTP will lead to the improvement of the O&M and accordingly, to a better performance of the WWTP.

Almost a third of the inhabitants in San Pedro Magisterio are connected to the WWTP “Friuli” and produce an incoming wastewater flow of 1,11 L/s (96 m^3/d) which is 31 % of the design flow. After connecting all households in the neighbourhood, there will be capacity for 136 more households.

As for San Pedro Magisterio, the points of sampling were also for this WWTP the in- and outlet resulting in the unknown of the removal efficiency of the pre-treatment for oil and greases and TSS. After passing the pre- and primary treatment, the wastewater contains 36 % less oil and greases and 35 % less TSS. During the entire treatment process, oil and greases are removed by 44 % and the TSS by 76 % which fulfils the guideline value (see Figure 36). Same accounts for the removal efficiency of 61 % for COD. Even though the organics are removed more efficiently than in El Paso, the removal efficiency of 80 % for BOD_5 is still below the European Union law recommendation as well as below the Swedish EPA value. Equally to El Paso, there is neither information about the sensitivity of the Río Rocha, which is the recipient water, nor details about the use of the water downstream. Turning now to the removal efficiency of the nutrients, due to a lack of data for the concentration of total organic nitrogen in in- and effluent, it was not possible to calculate its removal efficiency. The phosphorus is reduced by 41 % which is slightly more than 50 % of the required efficiency. Figure 36 presents the removal efficiencies achieved at the WWTP compared to the recommended ones.

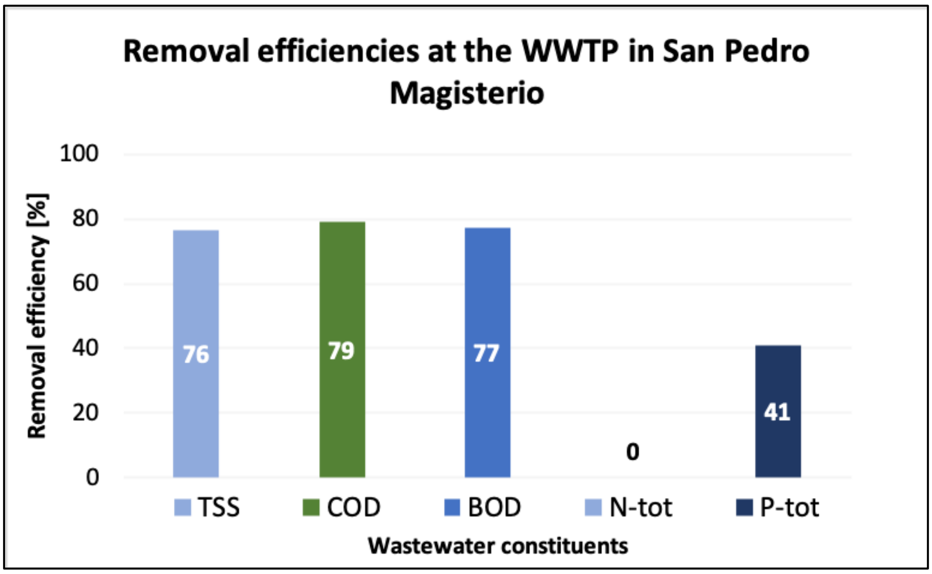


Figure 36: The removal efficiencies in [%] of the wastewater constituents through the entire treatment at the WWTP in San Pedro Magisterio (in columns) and the guideline values according to the European Union law from 1991 (red lines).

It took one year from the planning to the start of the treatment of wastewater through the WWTP and its construction was reviewed as uncomplicated. According to the operator and the administrative unit of the WWTP, the design was well elaborated, and the infrastructure facilitates the carrying out of O&M. However, the O&M duties are perceived as difficult by the operator because of the manual cleaning of screens and sedimentation channels. Contrary to El Paso, the cleaning of the UASB reactor seems not to be a difficulty for the operator; at least not consciously since regardless of his own evaluation, the reactor is questioned to be working due to the absence of produced sludge.

An engineer from SEMAPA is working voluntarily at the WWTP a few times a month and the administrative unit stated that, including the engineer, no other personnel is needed. This engineer also carries out the training in case a new operator is hired.

In both WWTPs the design flow is not exhausted yet and given that, the expansion of the neighbourhood and consequently, the connection of further households could be covered. Nevertheless, in neither of the two WWTPs exists a manual for O&M that may help to improve the technical performance of the treatment and ensure the reliability of the system.

The environmental dimension (*Table 13* in Appendix C)

Both in El Paso and San Pedro Magisterio, methane is produced during the anaerobic treatment in the UASB reactor but because of the small quantity, it is burned directly. In El Paso, the sludge produced is dried and is, then, picked-up for disposal while no sludge produced at the WWTP of San Pedro Magisterio. As already mentioned in the economic dimension, no material, no energy and no fresh water is consumed at neither of the WWTPs. The use of chemicals is practised at El Paso but in very small quantities that are, according to the engineer, neglectable.

The maximal permitted concentrations according to the Ley 1333 were retrieved from *Table 4* in Section 3.2.2 and in Figure 37, the determined values determined for the effluent quality of both WWTPs were compared to those limit values.

The nutrients are not recovered but remain to large extent in the wastewater which is in both cases reused downstream, unsupervised, for the irrigational purpose. The concentration of total phosphorus in El Paso accounts to 17,7 mg P/L and is almost nine times the maximal allowed concentration. The concentration of total nitrogen discharged to the recipient water is very high with 116,78 mg N/L which lies ten times higher than the permitted concentration of 12 mg N/L. For the effluent in San Pedro Magisterio, however, no data was available for the total organic nitrogen content in the effluent and hence, no concentration of the total nitrogen could be calculated. The phosphorus concentration is lower than in El Paso, but with 11 mg P/L still more than 5 times higher than the permitted concentration.

The treated wastewater leaving the WWTP in El Paso contains 71 mg SS/L which exceeds the allowed concentration of 60 mg SS/L by 11 mg/L. The COD was measured to be 253,5 mg O_2/L in the effluent what is only 3,5 mg O_2/L too high. However, the determined BOD$_5$ is with 168 mg O_2/L very high and more than double of the limit value. A totally different result was found at San Pedro Magisterio, where the maximum BOD$_5$ is only exceeded by 2 mg O_2/L. Here, the concentration found for the COD in the effluent is with 123 mg O_2/L half of the concentration permitted. The amount of TSS is quite high with 82 mg SS/L.

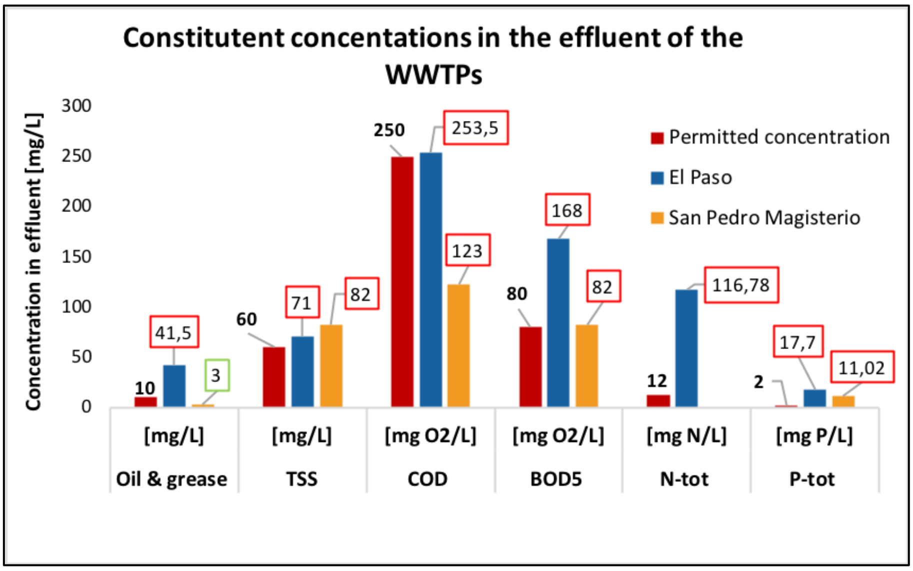


Figure 37: The concentrations of wastewater constituents in the effluent discharged from the two investigated WWTPs. In red boxes the concentrations exceeding the permitted value given by the Ley 1333 and in green boxes the ones within the allowed limits.

The wastewater effluent at the WWTP at El Paso contains 3,53*10^6 UFC/ 100 mL and at San Pedro Magisterio 1,00*10^7 UFC/ 100 mL. Both are much higher than the permitted maximal concentration of 1*10^3 UFC/ 100 mL (see Figure 38). During heavy rain in the summer season, wastewater with a concentration of 3,57*10^7 at El Paso and

4,80*10^7 UFC/ 100 mL at San Pedro Magisterio is discharged over the by-pass to the streams without passing the primary, secondary, not tertiary treatment unit.

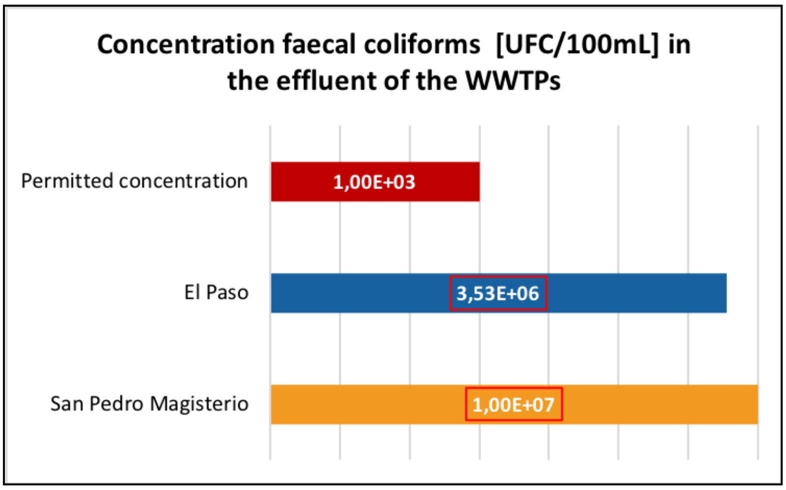


Figure 38: The concentration of faecal coliforms in the effluent discharged from the two investigated wastewater treatment plants.

The area occupied by the WWTPs is an important indicator when related to the design flow. For El Paso, the area required accounts to 2 974 m^2 which can be pictured as 3,41 $m^2_{area}/m^3_{wastewater, design}$. The total area available offers 7102 m^2 and therefore, 58 % is still available. In San Pedro Magisterio 4,8 $m^2_{area}/m^3_{wastewater, design}$ is needed due to an occupied area of 1 493 m^2, and 77 % of the total area is already used.

Both treatment plants are located in a peri-urban area and the houses are built relatively close to the treatment plants, as e.g. the nearest house can be found 50 m away from the WWTP's ground in El Paso and in around 100 m distance in San Pedro Magisterio.

The social dimension (*Table 14* in Appendix C)

There was a sense of high awareness amongst the interviewees in both neighbourhoods. All participants knew about the importance of the treatment of wastewater for the protection of health and the environment. Only a few have heard of cases in which people suffered illness due to the bad quality of the stream water. At both locations, more than two-thirds of the households participating in the survey responded that illness in form of infection an impact caused by the release of untreated wastewater to the environment. Additionally, they mentioned the contamination of freshwater bodies and the increased presence of mosquitos as consequences.

80 % of those who were interviewed were satisfied with the service provided by the WWTP in El Paso. In San Pedro Magisterio, 70 % of the participants were satisfied but despite, more than half (65 %) expressed precise complaints: 86 % criticised that the wastewater returns from the canalisation system in times of heavy rain and suggested the change of pipes as an improvement, and 14 % complained about the odour emitted

from the WWTP. Another necessary improvement was mentioned by 18 % and it was the higher purification of the wastewater before it is released to the environment. In El Paso, only 10 % have complaints, but also here, it was stated that the wastewater returns during the rainy season from the collection system. For this reason, the change of pipes was mentioned by 35 % as necessary and 57 % wanted all households to be connected to the WWTP. The sewage-coverage accounts to 44,5 % of the households and of the residents interviewed, 15 % were not connected. Some stated they asked for being connected but have not heard back from the association for over half a year. In San Pedro Magisterio, all households are connected to the drinking water system, but only 56 % to the sewage system. Yet, all houses that the surveys were conducted at were provided with a sewage system connection. The tariff collected for the sewage service is included in the price for the drinking water service. In San Pedro Magisterio the price is a result of 60 % of the amount of drinking water consumed times a fee per litre depending on this amount. There are three categories: low, medium and high consumption. To calculate the average price, the fee for the medium consumption was used. Whereas the average price is 9,81 Bs/month according to the survey answers, the average price calculated with the price list provided by the association was 3 Bs/month. By all users participating in the survey, the price was perceived as justified and 55 % were willing to pay more if their suggested improvements would be realised. In El Paso, the price is fixed with 5 Bs/month. There, however, many people did not know that they pay or how much they pay. Because of this, the overall response rate regarding the price itself was poor and of those one rated the price as justified, two as too low and two as too high. Independently from the knowledge about the tariff, 45 % were willing to pay more in case of the enhancement of the service.

The emissions in form of odour, noise and visual impact noticed by the inhabitants are crucial to interpret the acceptance of the WWTP and the related complaints. In El Paso, 50 % of the people were sensing odour outgoing from the WWTP and 30 % of them find it disturbing in their everyday life, especially during the night and in the mornings. Contrary, noise does not seem to be seen a problem amongst the interviewees and 30 % stated the WWTP has a visual impact but it does not disturb them during their everyday life. In San Pedro Magisterio, the appearance of the WWTP was perceived from 20 % as positive because the ground around the treatment plant that was inaccessible before is now used as a recreational area. Different though for the emitted odour: 45 % reported to have noticed it and all of those have perceived it as irritating, especially when the air is warm and in the mornings.

The following Figure 39 provides an overview of the responses given by the residents that were participating in the survey. The obtained qualitative data is illustrated as percentage of the application with the corresponding indicator.

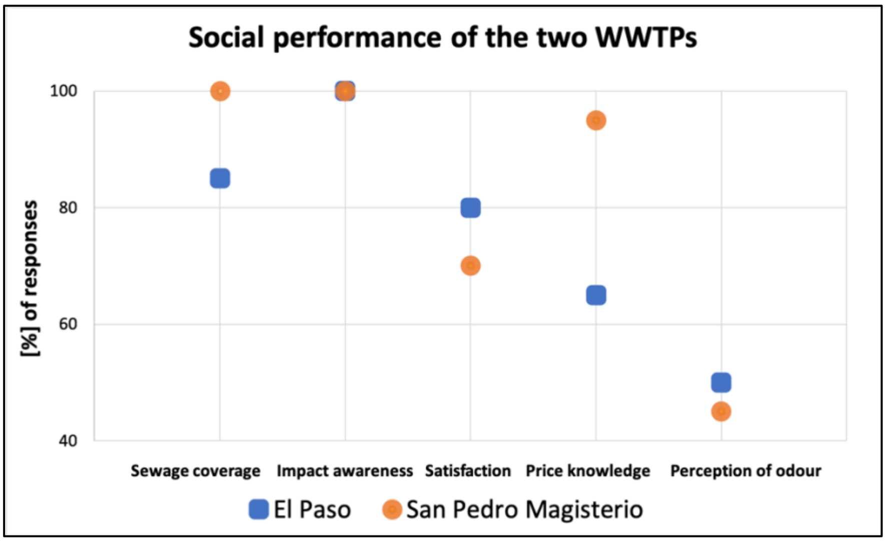


Figure 39: Social performance of the WWTPs in terms of sewage coverage, the awareness of the impact of untreated wastewater released to the environment, satisfaction with the sewage service, the awareness of the price paid for the service, the perception of odour.

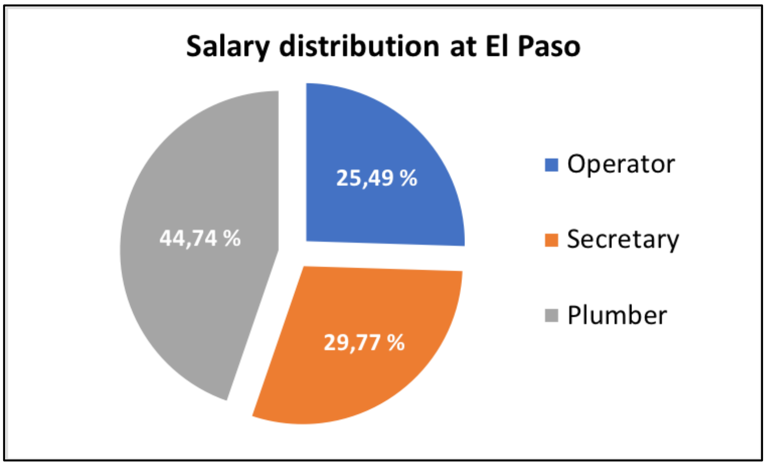
The institutional dimension (*Table 15* in Appendix C)

The WWTP in El Paso can sustain itself with the income from the tariffs from both wastewater and drinking water service fees. They plan to increase the price per m^3 wastewater to cover the operational costs only from the money paid for this service. In San Pedro Magisterio they did not know if the costs are covered only by the income through the fee for the wastewater service. They also want to increase the prices to realise the improvement of the system. In both plants, events to communicate with the users are organised once a year and all of them are recorded.

The questions regarding the level of institutional capacity characterized by the availability of technical and administrative human resources, and of enough supplies and equipment were affirmed both by the administrative unit at El Paso, as well as at San Pedro Magisterio. However, both specified their answers by mentioning there are enough technical human resources when counting the engineers as permanent employees. Furthermore, at El Paso, equipment is missing, and at San Pedro Magisterio, the operator is complaining about not having a set of working clothes to change and neither does he have a protective mask. Hence, there is a lack of safety clothes.

The incoming flow to the plants is not recorded and the quality of in- and effluent is not analysed, but once a year the engineer measures the flow in El Paso, and respectively, the university does it in San Pedro Magisterio and also analysis the quality at both WWTPs. The results are recorded but the data is not stored by association but by the university.

The pie charts in Figure 40 shows the breakdown of the salary per hour earned by the permanent employees at the two WWTPs. The bigger the pie piece, the high the employee's hourly payment in comparison to the ones of the other employees.



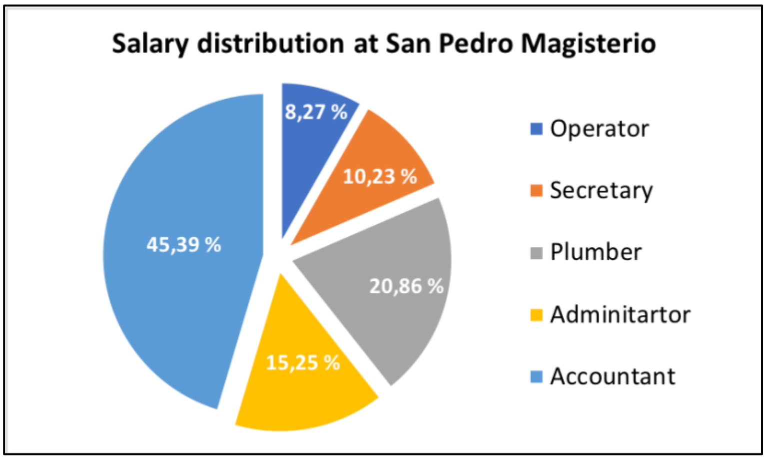


Figure 40: The salary distribution as percentages of the sum of hourly payment at the WWTPs (El Paso on top, San Pedro Magisterio on the bottom).

The average salary 2,03 US-$/hour for someone working at the WWTP of El Paso. The plumber and the secretary earn 2,72 US-$/hour and 1,81 US-$/hour and both work 8h/day from Monday to Friday, while the operator earns the least with 1,55 works US-$/hour but works the most with 8h/day on every day of the week. An additional important information is that the operator lives on the ground of the WWTP, less than 20 m from the treatment units, to be always at site, while his family lives about 10 min away. He complains about suffering from a strong headache.

The average salary is 3,99 US-$/hour for an employee working at the WWTP of San Pedro Magisterio. The accountant working 8 h/month at San Pedro Magisterio earns with 9 US-$/hour double the amount of 4,16 US-$/hour which is what the administrator earns who works 4h on five days of the week. The lowest payment is received by the operator. He works every week 8 h/day from Monday to Friday and 4 h on Saturday and earns 1,65 US-$/hour. Hence, the employee working the most has the lowest payment per hour.

5.2.3 Summary of the assessment

In conclusion, the sustainability of the two WWTPs was difficult to assess and there is no value for the global sustainability available to answer the question of their sustainability with “yes” or “no”. With regard to the five dimensions, there was too little data available to give a statement about the economic sustainability, the technical sustainability was rather low at both WWTPs in terms of resource recovery, the environmental performance is low and effluent quality but higher for its low consumption of resources. The interpretation of the social dimension is based on subjective data and its performance overall is considered high. The institutional sustainability is due to the evaluation of the questionnaires high, but the recent implementation of this aspect is connected with an uncertain outcome due to the untested approach to acquire its indicators.

The WWTPs are based on anaerobic processes that provide a resource preserving treatment of the wastewater resulting in low consumption of energy, water, chemicals and materials. Despite the potential of recovering resources as nutrients, biogas, sludge and wastewater, it is not utilised to compensate O&M costs. The chosen technologies are appropriate for the implementation in a developing country for the possibility to be constructed with local resources and a low level of sophistication which should come along with simple O&M if appropriately implemented. Nevertheless, their weaknesses were connected to the complexity of the O&M due to poor designing of the WWTPs and the lack of institutional capacity, causing that the staff did not receive the required training to execute the duties. The consequences are low removal efficiencies and an insufficient quality of the effluent. Here, especially the nutrients are problematic because they pose the risk of eutrophication on the aquatic ecosystems connected to the recipient water. The treatment through the UASB reactor offers the possibility of nutrients recovery and wastewater reuse; however, the concentration of faecal coliforms in the effluent must be reduced by more than four log removal and currently only one is achieved. In El Paso, this problem is addressed by implementing a new treatment unit after the UASB reactor to reduce the load of TSS entering the anaerobic filters and hence, to prevent their clogging. Its higher efficiency and the UV penetration during the retention in the maturation ponds due to less particles will result in higher in higher log removals of pathogens.

Another weakness within the technical unit was identified due to low salaries and its unequitable distribution.

The residents of the neighbourhoods were aware of the importance of the wastewater treatment systems and only few complaints were expressed despite the closeness of the WWTPs to their homes. The satisfaction, however, is strongly affected by the low sewage coverage rate, leaving many households disconnected. Another negative impact is the returning of the wastewater from the canalisation during heavy rains. Those also cause the flooding of the WWTPs and the direct release of the wastewater to the streams.

5.2.4 Comparison of the two WWTPs

Following the same procedure as in the last two sections, the results for the comparison of the two WWTPs are presented for each dimension separately. For the direct comparison, a score of 0 or 1 was assigned, with 1 as the better score excelling 0. To ensure that the scores were assigned correctly, the indicator's positive or negative impact on sustainable development was considered. In the case of equal results, the WWTPs were assigned 0,5 points and if there is a lack of information, this WWTP received 0 points while the other WWTPs automatically got one point regardless of its performance. The difference between the sum of points gained by the WWTPs reveals how superior the WWTP with a higher sum is performing within the corresponding dimension.

Figures 42 to 46 in this section compare the performances of the two WWTPs. The dark colour is representing the performance of the WWTP of El Paso (EP) and the light the WWTP of San Pedro Magisterio (SPM).

The overall outcome is summarized in Figure 41 and it can be seen that the WWTP in El Paso is performing better within the economic and technical dimension while the WWTP in San Pedro Magisterio scores higher for the indicators of the environmental and social dimension. They tie in terms of institutional performance. After summing up all points for each WWTP, both have 30,5 points.

According to this result, the sustainability performance of both WWTPs is equal. Neither can be said if the performance is actually sustainable or not nor can the difference in the performance itself for a single indicator be told. Additionally, the significance of the single indicators for a sustainable system were ignored. To overcome this limitation, the ranks obtained for each indicator according to Section 3.3.1 which were used for the identification of the significant indicators within the set were multiplied with the scores assigned to each WWTP in the chapter. The new scores are 15,32 points for the WWTP of El Paso and 14,10 points for the WWTP of San Pedro Magisterio.

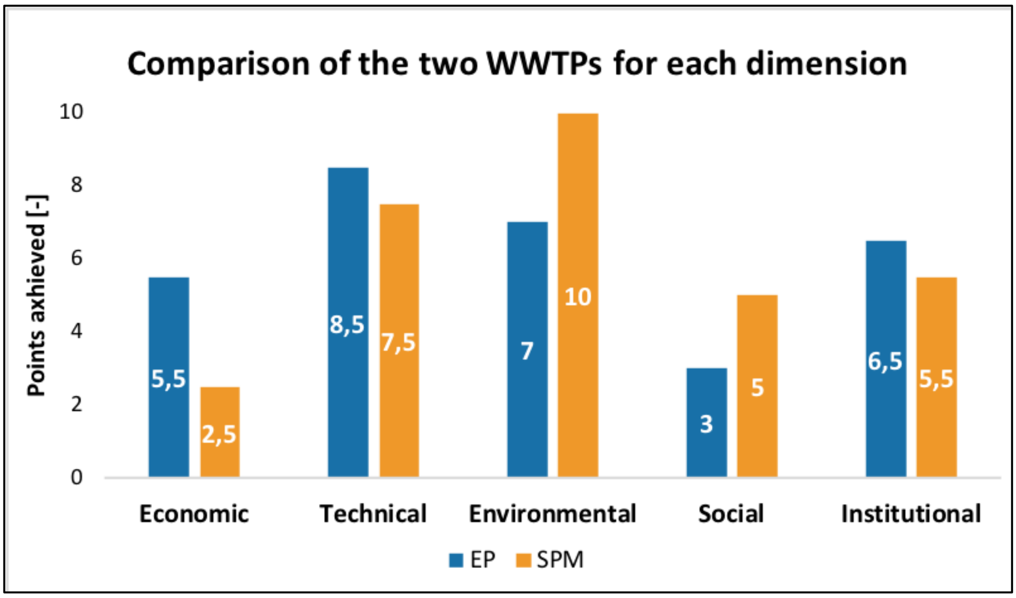


Figure 41: The overall performance of the WWTPs. For each dimension, the bars represent the sum of points of the WWTP in El Paso (blue) and in San Pedro Magisterio (orange).

The economic dimension

After counting the points, the WWTP of El Paso received 5,5 points while it was 2,5 for the WWTP of San Pedro Magisterio (see *Table 16* in Appendix D). This outcome is illustrated in Figure 42 where dark orange bars correspond to the WWTP in El Paso and dominate the light orange bars that represent the WWTP in San Pedro Magisterio.

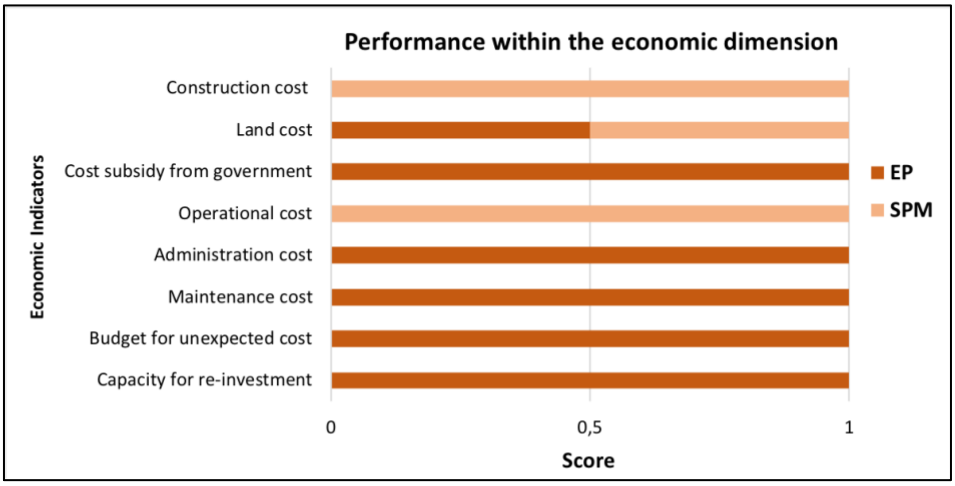


Figure 42: The economic performance of the WWTPs in comparison. Each bar represents the score obtained regarding one indicator. The light orange bars represent the WWTP in San Pedro Magisterio (SPM) and the dark orange bars the WWTP in El Paso (EP).

When comparing the two WWTPs in terms of costs spent for the initial phase, the treatment plant in San Pedro Magisterio was cheaper; however, 0 % were subsidised by the government whereas in El Paso 42,86 % were subsidised. At both plants, the land was provided free of charge. Hence, they tie within this criterion.

Due to a lack of information at San Pedro Magisterio and higher monthly expenses, El Paso scores higher for the criteria of operation and maintenance costs and the capacity of reinvestment. Even though the budget available for expansion or for emergency cases is 0 US-$ but the administrative unit is aware of the non-existence.

The technical dimension

As a consequence of a greater number of indicators within this dimension, the sum of points is higher than for the economic dimension and accounts for 9 for El Paso and 8 for San Pedro Magisterio. In Figure 43, it can be seen how close the result is since it is difficult to identify which colour is dominating, but the exact points can be retrieved from *Table 17* in Appendix D.

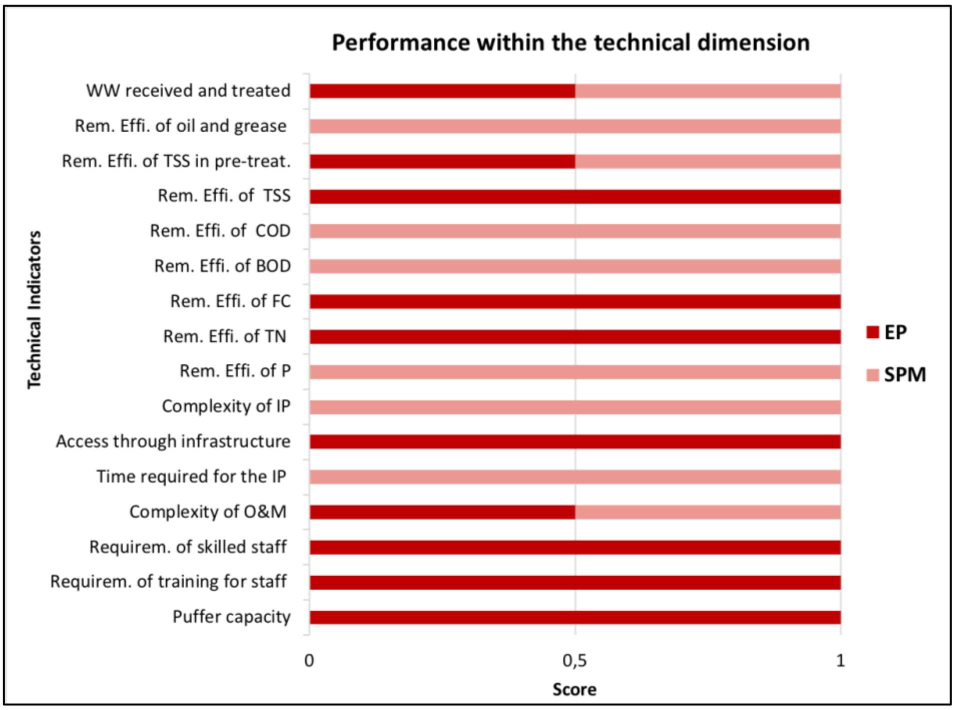


Figure 43: The technical performance of the WWTPs in comparison. Each bar represents the score obtained regarding one indicator. The light red bars represent the WWTP in San Pedro Magisterio (SPM) and the dark red bars the WWTP in El Paso (EP).

The impact of the indicator *amount of wastewater treated and received* was hard to determine since it is influenced by the total amount of wastewater produced, the number of households connected, the once to be connected, the growth rate of the area and the treatment efficiency of the plant. These aspects were reviewed separately through several indicators and thus, here the indicator was rated neutral and both WWTPs receive 0,5 points. The treatment efficiency is slightly higher at the WWTP of San Pedro Magisterio which scores 4,5 compared to 3,5 points at El Paso. The initial phase was less complicated at San Pedro Magisterio, but the accessibility provided to facilitate the O&M is better at El Paso. The buffer capacity available at the WWTP of El Paso is almost double the one at the WWTP of San Pedro Magisterio.

The environmental dimension

The total number of points received for the environmental performance accounts for 7 for the WWTP in El Paso and 10 for the one in San Pedro Magisterio. *Table 18* in Appendix D and Figure 44 show the equal performance of the two WWTPs for most of the indicators.

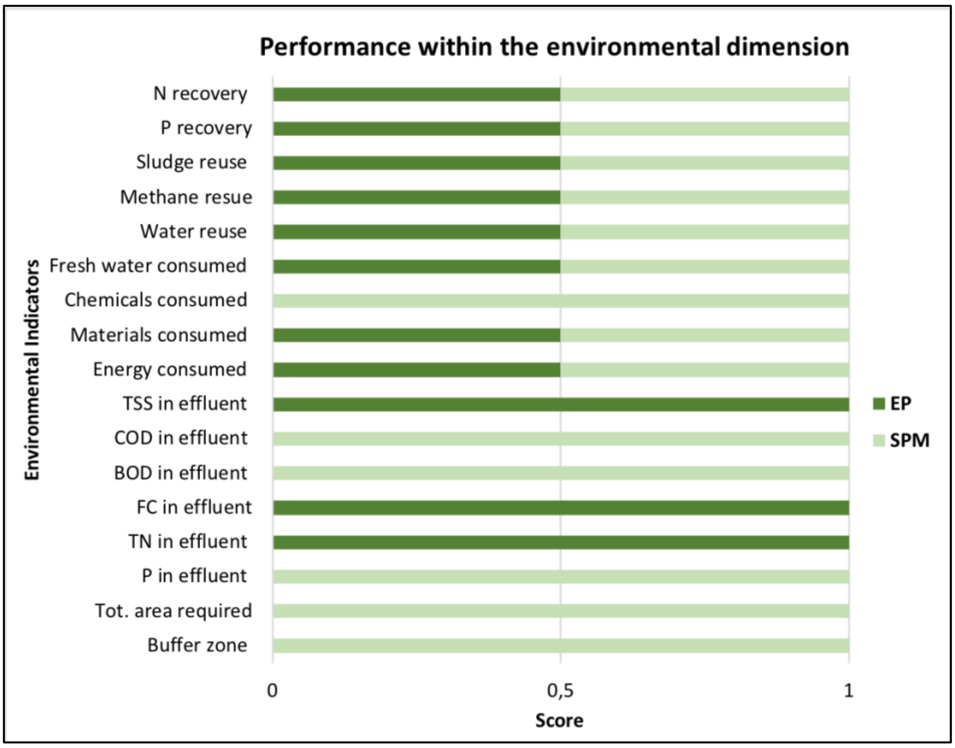


Figure 44: The environmental performance of the WWTPs in comparison. Each bar represents the score obtained regarding one indicator. The light green bars represent the WWTP in San Pedro Magisterio (SPM) and the dark green bars the WWTP in El Paso (EP).

The difference of 3 points is made by the smaller land requirement of the WWTP in San Pedro Magisterio and the greater distance between the facility and the closest houses. Moreover, there are chemicals used during the treatment procedure in El Paso, but there is no information available regarding the quantity they are used in.

The concentrations of wastewater constituents in the effluent is not compared to the limit values but the quality of the two WWTP's effluents are directly compared to each other. The concentrations of TSS, faecal coliforms and total nitrogen are lower in the effluent discharged to the Río Mal Pasomayu in El Paso and the concentrations of COD, BOD and phosphorus are lower in the effluent discharged to the Río Rocha in San Pedro Magisterio.

The social dimension

When it comes to the consideration of the social indicators, the WWTP in San Pedro Magisterio performs better, achieving 5 points while the one in El Paso received 3 points (see *Table 19* in Appendix D and Figure 45).

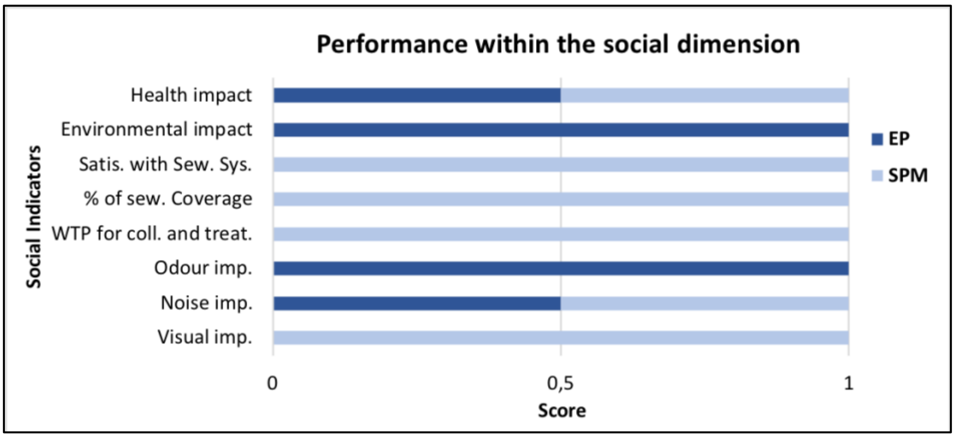


Figure 45: The social performance of the WWTPs in comparison. Each bar represents the score obtained regarding one indicator. The light blue bars represent the WWTP in San Pedro Magisterio (SPM) and the dark blue bars the WWTP in El Paso (EP).

The residents of both neighbourhoods are aware of the potential health impacts connected to the release of untreated wastewater to the environment. Only 2 % make the difference in terms of the awareness of the impact on the environment. The sewage coverage within the neighbourhoods is 11 % higher in San Pedro Magisterio than in El Paso. Here is also where more people are satisfied with the sewage system and are willing to pay a tariff for the service. The perceived odour was disturbing for households located close to the WWTP in El Paso while houses located further away were unaffected, but in San Pedro Magisterio where the WWTP is located close to the quite dense housing area complaints about odour emission were expressed throughout all inhabitants and 30 % more households than in El Paso complained about odour disturbing their everyday life. While the visual impact was described as positive by some households in San Pedro Magisterio, 30 % of the questioned households in El Paso stated a negative opinion.

The institutional dimension

The institutional performance of the two WWTPs differs by one point: 6,5 points for El Paso and 5,5 points for San Pedro Magisterio (see *Table 19* in Appendix D and Figure 46). For the criteria of the institutional capacity, the records of data and the interaction with users, the performance is equal. The employees at the WWTP in San Pedro Magisterio gain more money per hour, but the safety conditions are better at the WWTP of El Paso. While there is no information available about the auto-sustaining of the sewage system in San Pedro Magisterio, the plant in El Paso can be sustained with help of the income from the drinking water system.

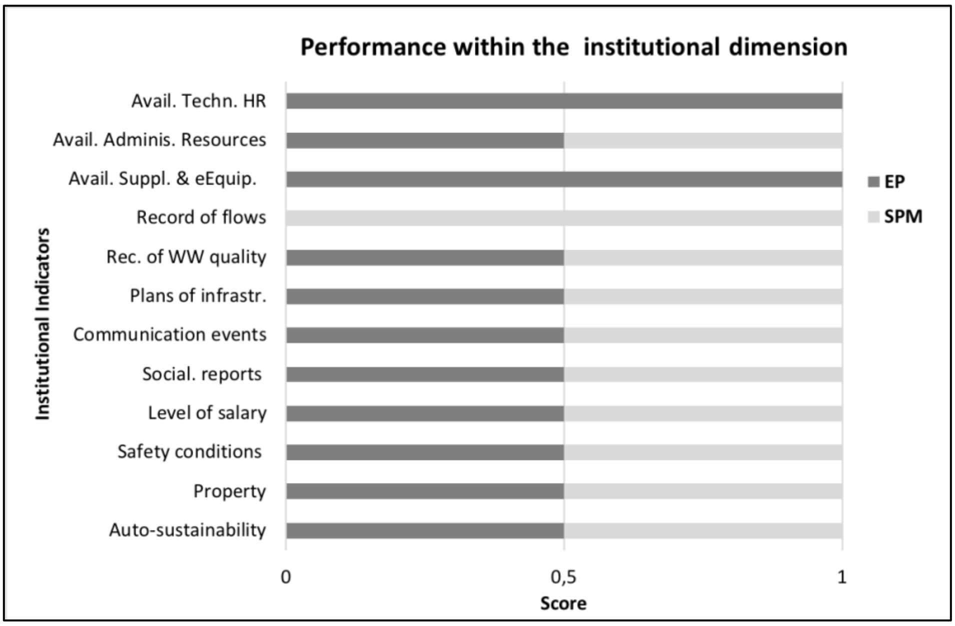


Figure 46: The institutional performance of the WWTPs in comparison. Each bar represents the score obtained regarding one indicator. The light grey bars represent the WWTP in San Pedro Magisterio (SPM) and the dark grey bars the WWTP in El Paso (EP).

5.3 Identification of significant SDIs in developing countries

After using the set of SDIs to assess the sustainability performance of two WWTPs in a developing country, experts from different backgrounds but strongly familiar with the concept of sustainability and some specialised in wastewater engineering were consulted to rank the indicators within the five dimensions. The outcome is a list of SDIs that are significant for achieving sustainable wastewater treatment in developing countries.

In *Table 20* in Appendix E the normalised average ranks over the entire set of indicators (see Figure 52a to 52e in Appendix E) as well as for each dimension (see Figure 53a to 53e in Appendix E) are presented. The indicators receiving a 0 are the lowest and the ones receiving a 1 are the highest ranked indicators. Within the total set of SDIs, the indicators perceived as more, and the ones perceived as less important were identified by using a 25 % - quantile.

The light grey marked, and black written numbers are the ones ranked highest and the normalised ranks can be withdrawn from the Figure 47. There are two economic, two technical and one institutional indicator but no social indicator included in this list. The most significant indicators within the set of SDIs are listed from highest rank downward:

- ***available technical human resources***
- ***operational cost***
- ***amount of wastewater treated and received***
- ***complexity of O&M***
- ***maintenance cost.***

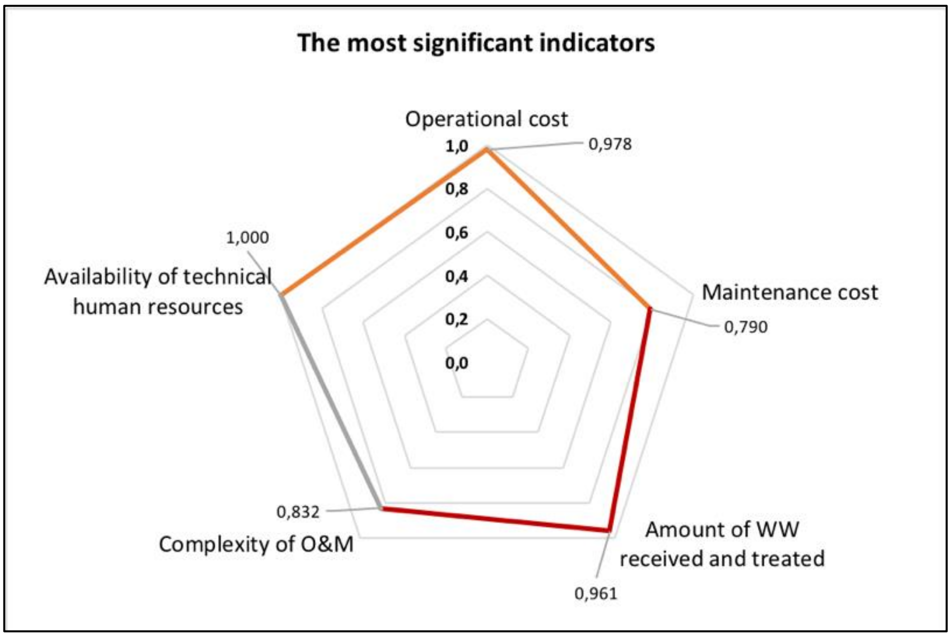


Figure 47: The indicators ranked as most important for the sustainability of WWTPs within the entire set of SDIs.

The dark grey marked, and white written numbers are the ones ranked lowest. The concerned indicators are presented in Figure 48 and listed in the following from lowest rank upward:

- *property of land and fixed activities*
- *visual impact*
- *number of annual socialized reports with users*
- *removal efficiency for phosphorus*
- *money available to reinvest*
- *noise emission*
- *plans of the infrastructure*
- *land cost*
- *removal efficiency of TSS*
- *buffer capacity*
- *number of communication events with users*
- *removal efficiency of nitrogen*
- *methane reuse*
- *cost subsidy by the government*
- *construction cost*
- *removal efficiency of TSS during pre-treatment*
- *willingness to pay for the sewage service*
- *buffer zone.*

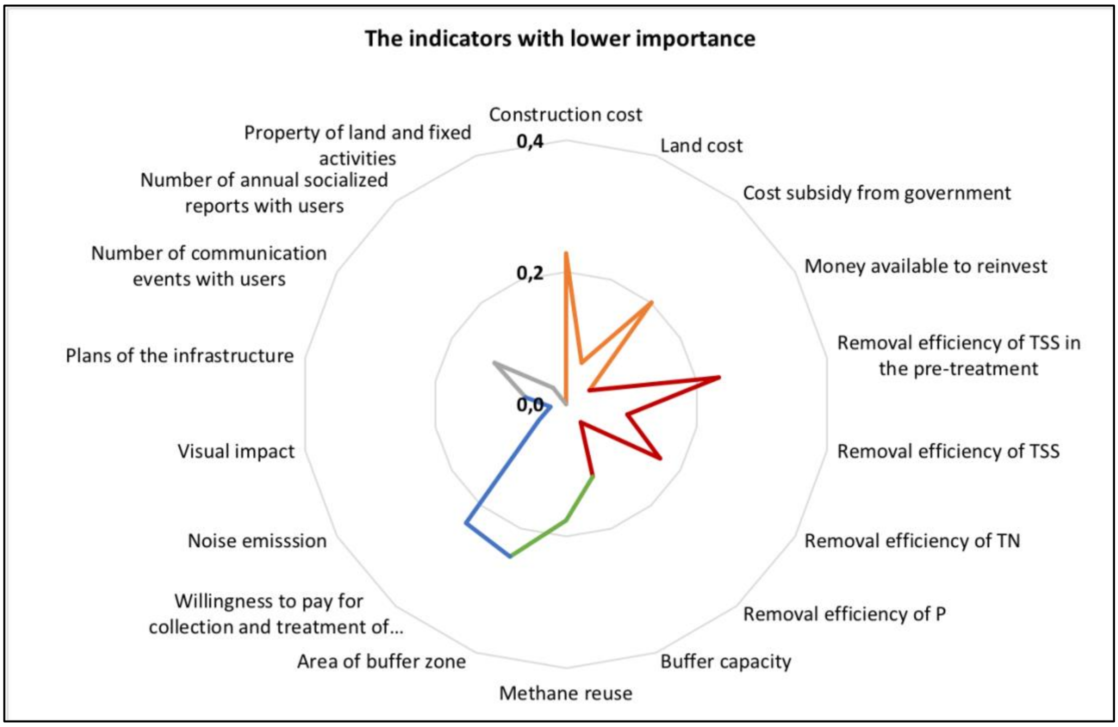


Figure 48: The indicators ranked as least important for the sustainability of WWTPs within the set of SDIs.

The perceived importance of the dimensions, as presented in Figure 49, was obtained by assigning points to each dimension and normalising their sum. The institutional dimension scored highest and its normalised values is 1. The environmental dimension scored lowest and its normalised value is 0. The normalised values of economic, technical and social dimension are 0,5, 0,43, 0,57.

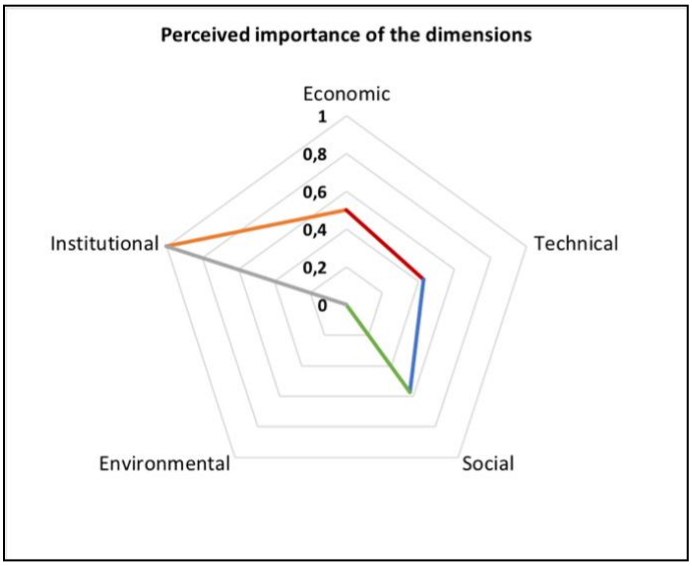


Figure 49: The perceived importance for the five dimensions of sustainability.

The low and high perceived importance of the indicators within the corresponding dimensions was determined. The Figures 52a to 52e in Appendix E have the same shape as the Figure 53a to 53e in Appendix E that show the normalised score for the total set of indicators. However, here one indicator in each dimension gets a 1 and respectively, one indicator gets a 0. In this way, it is easier to identify the significant and the less important indicators:

- Within the economic dimension the indicator of “the money available to reinvest” received the lowest and the “operational cost” the highest rank (Figure 53a in Appendix E).
- Within the technical dimension the indicator of “the amount of WW received and treated” received the lowest and the “removal efficiency of phosphorus” the highest rank (Figure 53b in Appendix E).
- Within the environmental dimension the indicator of “methane reuse” received the lowest and the “FC in effluent” the highest rank (Figure 53c in Appendix E).
- Within the social dimension the indicator of “visual impact” received the lowest and the “awareness of the health impact” the highest rank (Figure 53d in Appendix E).
- Within the institutional dimension the indicator of “property of land and fixed activities” received the lowest and the “availability of technical human resources” the highest rank (Figure 53e in Appendix E).

6 Discussion

This chapter is divided into the assessment, the sustainability performance of the two WWTPs, their comparison, the identification of significant SDIs and at last, the limitations of this study.

6.1 The assessment

Based on several studies, it is assumed that many indicators of the set are important for the assessment of the sustainability of WWTPs in developing countries; however, depending on the location special attention must be paid to some of them and others may be neglected (Bradley et al., 2002; Muga and Mihelcic, 2008; Singhirunnusorn and Stenstrom, 2009). In their research, Muga and Mihelcic (2008) emphasize: "*The selection and interpretation of indicators are influenced by an area's geography and demography*". In line with this, the elimination of indicators depends highly on the given size of the population, the economic situation, the climate condition, the availability of resources and the sensitivity of recipient water or the potential purposes for reuse. For example, the criterion of "Resource Recovery" includes the indicators *Phosphorus, Biogas, Sludge reuse and Water reuse*. If there is no anaerobic digestion, the production of biogas might not be feasible as an energy source. Additionally, the lack of data records may lead to inaccurate data acquisition and hence, to a false notion about the sustainability of the system.

In consideration of this, the final set used in this study may still be too extensive. Time that can be saved by selecting the relevant indicators and hence, the avoiding data acquisition for irrelevant indicators is crucial since it is connected with labour costs (Muga and Mihelcic, 2008). Firstly, a pre-study could be performed through a checklist or set of obvious or easily visible indicators corresponding to minimum requirements, e.g. water flow through the WWTP, maintenance of the WWTP and availability of economic records. If these minimum requirements are not met, the WWTP can directly be deemed unsustainable. A further assessment would only be done when these minimum requirements are met. In addition, by the conduction of a detailed pre-study, the unnecessary inclusion of indicators could have been avoided and hence, the time of investigation in form of performing interviews and analyses could have been reduced. An example is the land cost which is non-existent in both cases due to the provision of ground, free of charge, by the communities. It was also known that no nutrients are recovered at the neither of the two WWTPs. Nevertheless, the corresponding indicators were included to also discuss the matter due to the recommendations given by many scientists, as Bakir (2001), Singhirunnusorn and Stenstrom (2009) and Andersson et al. (2016), that the recovery and reuse of resources contained in the wastewater is a key to sustainable development and may, according to Verbyla et al. (2013), be the solution for global food security. All factors mentioned in the set of SDIs elaborated in Section 5.1 are relevant for sustainable wastewater treatment systems; however, depending on the system configuration and the present regulations, not all indicators are significant for every treatment system.

Challenges

The first aim of this study sought to identify a set of sustainability indicators that are relevant for sustainable small wastewater treatment systems and the indicators included in this set were presented and shortly discussed within Section 5.1 but some challenges when choosing the indicators are briefly described in the following and put in context with previous studies.

The total set yields to cover every aspect of sustainability; however, since there are so many factors to consider, the completeness of the set must be reviewed and continuously improved. Due to the limited expertise and time, the indicators were chosen based on literature studies. As Hellström et al. (2000) pointed out, the indicators are often hard to be seen as positive or negative in terms of their impact on sustainability, hence they are often used to compare the performance of several systems. This procedure was followed in several previous studies, as e.g. by Molionos-Senante et al. (2014) and by Muga and Mihelcic (2008) who compared different wastewater treatment technologies in terms of their level of sustainability. While indicators addressing the effluent quality can, in most cases, be compared with the limit values stated in the law, the benchmarking is much more difficult for other indicators and very little was found in the literature. An example of the challenge to formulate benchmarks are the costs of a WWTP. Those are directly limited by the amount of money available but are influenced by the requirements for the effluent quality, the amount of wastewater to be treated, the ability of the users to pay for the ongoing costs and the location, hence, material and labour cost. As a consequence, those indicators can be only discussed in comparison to other systems with the same set-up.

Another challenge was the avoidance of repetition of indicators within the set. Due to the high interconnectivity between the dimensions, the same indicator is assessed by collecting information within two different aspects, hence one indicator may be included in different dimensions to address another aspect but is based on the same data, causing the disadvantage of double count the data. Some examples are removal efficiency and effluent quality; administrative costs and salary; auto-sustaining of the plant and tariff for the service and operational costs. The removal efficiency picks up again the information about the effluent quality even though here in another context. From this, it follows that the same data is used repeatedly to interpret another aspect of sustainability.

The above applies to indicators that in the great context of the sustainability of the entire system may include information that is counted twice; however, the indicators reveal the sustainability within the corresponding dimension. Apart from those, there are also indicators within the same dimension addressing the same problem, as e.g. the *requirement of skilled staff* and the *requirement of training for staff*. In the end, if there is no skilled staff training is needed or the employment of an already trained worker.

The same accounts vice versa: the need for training means that there is a lack of skilled staff. To overcome this type falsification, those indicators should be merged.

Regarding the design of influence diagrams, the challenge of narrowing down all interconnections lead to confusion due to the fact that criteria and not indicators were used. The labelling was unfortunate as *the risk of eutrophication* is also part of the effluent quality but treated as an additional criterion. The same accounts for *the release of heavy metals*. To overcome this, an influence diagram addressing the indicators must be designed and the categorization in criteria and principle must be revised.

6.2 The sustainability performance of the two WWTPs

To assess the sustainability of the two investigated WWTPs, other studies were consulted as references to estimate if the obtained data for each indicator is to be considered to have a positive or negative impact on the sustainability performance of the WWTPs. At last, the result of the comparison of the WWTPs is shortly discussed.

Bolivia, as a developing country, finds itself as something called the infrastructure management gap (Verbyla et al., 2013). Even though many areas are densely populated, the resources to implement, operate and maintain centralized systems are missing (Massoud et al., 2009). As recorded by Singh and Kazmi (2018), this is also typical for systems in Asia where the focus is set on implementing cost-effective systems with a low environmental impact. Another limiting factor is that due to more urgent matters as political conflicts, supply of food and provision of health care, governments in developing countries pay little attention to sanitation services and Massoud et al. (2009) concluded: "*While there are many impediments and challenges concerning wastewater management in developing countries, these can be overcome by suitable planning and policy implementation*." This may be an explanation for what happened during the construction phase in El Paso. The time from planning until the start-up of the WWTP took 9 years due to bad planning. The plant was localised on a level higher than some households and hence, the pipe inclination was positive. As a result, the wastewater did not reach the WWTP. This resulted in extremely high investment costs because only the first construction was financed by subsidies Those wasteful errors must be avoided by structured planning and careful design.

On the other hand, a very positive finding was the availability of land and the provision free of charge by the community at both WWTPs which reduced the investment costs. Other costs are very low due to the biological treatment and hence, the absence of mechanical treatment units and pumps, no energy is consumed during the processes.

The incoming concentrations of most wastewater constituents at both WWTPs were found to be above the average concentration found in European domestic wastewater, presented by Roxendal (2012). The cause is the lower dilution of the wastewater due to reduced consumption of water at the interface level. At both WWTPs, the incoming wastewater is very high in TSS and their removal is especially important to protect the following technologies in the treatment chain and ensure their expected performance (Tilley et al., 2014). The removal efficiencies of pre- and primary treatment of TSS are relatively low but after the entire treatment and are within the guideline value (see Table 5 in Section 3.2.2).

One concerning finding is the low removal efficiency of organics at El Paso where an extremely low removal efficiency is reached. Also, at San Pedro Magisterio, the removal efficiency of BOD is lower than recommended, but the effluent quality in terms of discharged organics is met. Another is the low removal of nitrogen at El Paso, despite maturation ponds as final treatment unit. At San Pedro Magisterio, the removal efficiency of phosphorus is half of the recommended efficiency, but the most surprising finding is the negative efficiency at El Paso, i.e. more phosphorus leaves the WWTP than enters it. Unfortunately, the cause could not be identified.

At both WWTPs, the operator was trained by an engineer. Regardless, both operators were mentioning they have troubles with some tasks. In many other cases, the operator at WWTPs in developing countries are unqualified and this leads to malfunctioning of the system (Verbyla et al., 2013; WEF, 1992). Andersson et al. (2016) and Bassan et al. (2014) mentioned the lack of appropriate support by the government, powerless regulations and weak prosecution, and the low importance assigned to O&M as the main triggers. The findings of a study of WWTPs in Sri Lanka showed that also there, O&M are often inadequate (Sudasinghe et al., 2011). On the one side, at San Pedro Magisterio, the cleaning of the pre-treatment unit was described as the most complicated, but probably it is the most demanding unit, and on the other side, at El Paso, the UASB reactor was perceived as the most complicated to operate and maintain. The ladder was confirmed by the engineer working a few times a month at the WWTP who refers to the bad design of the reactor, making its operation complicated and burdensome. This is somewhat disappointing considering that the start-up of the WWTP was several years delayed.

During field visits in March 2018, several WWTPs in the Valle Alto, a valley located southeast of the city of Cochabamba, were inspected – the outcome was terrible. Besides the very well working WWTP of Cliza, only one WWTP could be considered in any way functioning; however, here, the pre-treatment, consisting of screens and sedimentation channels was overflowing due to a lack of cleaning. Furthermore, despite previous advice to avoid the keeping of animals on the terrain of the WWTP, a cow was grazing next to the waste stabilization ponds. The worst case was a WWTP found to be completely shut-down and this is not a single case: WWTPs in developing countries are often found to be abandoned (Verbyla et al., 2013). Bdour et al. (2007) conducted studies in the Middle East and found the same problems concerning the inadequate maintenance and the employment of unqualified staff in Palestine. Cossio et al. (2017) identified the lack of operational expertise as a reason for poor performance particularly for small WWTPs in Bolivia.

Another example within the department of Cochabamba was a WWTP where the operator has changed from one day to the other because the previous one did not show up. The new employee never worked at a WWTP before and no instructions were given to him. There was a dead dog in a maturation pond, a situation also experienced during other another case study in Peru conducted by Midkiff (2016). At the very WWTP, the growth of plants was so extensive that it, at first sight, seemed to be a planted wetland with subsurface flow even though it was a maturation pond.

A solution proposed by Massoud et al. (2009) is the centralised management to guarantee the control of O&M realisation. Moreover, and especially for wastewater treatment systems providing service to small populations, guidelines are considered to be an effective tool. Also, training of the employees and the assigning of responsibilities was found to be essential in developing countries by Sudasinghe et al. (2011) Murray and Drechsel (2011), and Massoud et al. (2009). Similar to the findings of Cossio et al. (2017) of the lack of a manual for O&M at many WWTPs in the department of Cochabamba, also at the two investigated WWTPs no written instructions on the execution of O&M duties or the frequency of those did exist.

The amount of excess sludge produced in the UASB reactor is normally very small (Letting et al., 1993) and this conforms to the finding at El Paso. However, the cause of the lack of production of sludge at San Pedro Magisterio is unknown and due to an expert's opinion, it may be the case that the microorganisms got flushed out from the sludge blanket during heavy rains, and hence, the treatment unit of the UASB reactor performs insufficiently. Both WWTPs have a UASB reactor as primary treatment unit and hence, a treatment technology that allows the recovery of biogas (Verbyla et al., 2013) and the production in place of the consumption of energy (Lettinga et al., 1993), and it offers the possibility of agricultural or aquaculture reuse (Bdour, 2007). Despite the advantages, none of the two WWTPs reuses the biogas; instead, it is burned due to the small quantity produced, as stated by the engineer. Studies conducted by Lettinga et al. (1993) showed that the implementation of UASB reactors with an appropriate post-treatment is a sustainable solution in tropical regions of developing countries. They pointed out the advantage of the flexible adjustments according to on- or off-site treatment of this technology.

In terms of the reuse of wastewater, the findings cannot be unambiguously interpreted due to a lack of information on the sensitivity of the recipient water bodies. Its availability is according to Massoud et al. (2009) of great importance for the entire system. Subsequently, also the potential risk of eutrophication due to the high released concentration of nutrients is unknown. However, the release of phosphorus is at both WWTPs and of nitrogen at El Paso exceeding the limit values. Verbyla et al. (2013) suggested the reuse of wastewater and the contained nutrients to allow the implementation of simplified treatment units that aim to remove pathogens rather than nutrients. Coming along with that, farmers benefit from better harvest, contributing to food security, and may increase their productivity and hence, improve the economic situation of the neighbourhood. In a region of Argentina, the use of wastewater for irrigation of different crops, wine grapes, fruits and vegetables led to an increased production and a flourishing economy; however, the negative impact is not well investigated at that specific site (Cavallini and Young, 2002). According to Angelakis et al. (1999), the provision of guidelines, as they exist in Israel, Italy, Jordan and Tunisia, enhances the planning and implementation of wastewater reuse for irrigational purposes. In the case of Israel, more than 15 years ago the reuse accounted for more than half of the domestic wastewater (Friedler, 2001).

Wastewater is used for the irrigational purpose in both neighbourhoods. Even though it is diluted after being released to the stream, the quality cannot be considered sufficient for all kinds of cultivations as stated by Alvaro Mercado in a personal conversation during a site visit in February 2018. Qadir et al. (2010) emphasised the need for performing risk assessments before reusing the wastewater to prevent harming environment and health.

At El Paso, the clogging of the anaerobic filters led to the conclusion that the concentration of TSS in the effluent from the UASB is too high and a sedimentation tank as additional treatment unit is currently in construction. A similar observation was done in San Pedro Magisterio where the space between the media of the constructed wetland was filled with particles. Despite these findings, the effluent concentrations of TSS are too high at both WWTPs. In previous investigations it was found that high TSS loadings are common in the effluent from a UASB reactor (Kahn, 2011).

During their investigation of treatment technologies in developing countries, Sperling and de Lemos Chernicharo (2002) assessed that with only the UASB reactor, no log removal of FC was achieved. The laboratory results revealed that only one log removal is achieved at El Paso and less than one log removal is accomplished at San Pedro Magisterio. According to Foresti et al. (2006), no pathogen removal can be expected by solemnly anaerobic treatment. Hence, the high concentrations in the effluent may be caused by a low efficiency of the sxmaturation ponds as post-treatment due to the insufficient preceding removal of particles which may protect viruses to be penetrated by the UV radiation of the sunlight (Symonds et al., 2014).

One of the most important findings is that at El Paso, where the BOD removal is expected to be high when looking at the technologies, it is double of what is permitted by law.

There is no nutrient removal achieved through an anaerobic treatment step and effluent concentrations vary. In Brazil, the reliability of several WWTPs was assessed by Oliveira and Sperling (2008). Some of those with a UASB reactor as primary treatment and a follow-up treatment in form of aerated filter, anaerobic filter, trickling filter, flotation unit, facultative and maturation pond. The findings were that except for phosphorus, the effluent standards were compiled for BOD, COD, and TSS. However, also here, the discharge of faecal coliforms was still too high.

Turning now to the discharge of nitrogen, at El Paso, it is ten times more than the permitted standard. For San Pedro Magisterio, the laboratory did, for unknown reasons, not measure the nitrogen concentrations. At both WWTPs, phosphorus is discharged in unacceptable amounts. The high concentrations of nutrients in the effluent may result in the contribution to eutrophication of downstream ecosystems and must be reduced if the wastewater will not be used for agriculture. The risk of eutrophication is, according to Rodriguez-Garcia et al. (2011) the greatest environmental impact of WWTPs and must be low and achieving the required effluent quality may demand the implementation of advanced technologies that cause high initial as well as O&M costs and are more difficult to operate (Verbyla et al., 2013). The operator needs to have more skills when advanced treatment technologies were implemented. To overcome these barriers, strengthened support by the government is required (Corcoran et al., 2010).

During heavy rains, the incoming wastewater is, partly in El Paso and entirely in San Pedro Magisterio, discharged untreated to the recipient water to prevent flooding and protect the UASB reactor. As a consequence, the discharged concentrations, despite the increased dilution through the great amount of precipitation water, are very high and severe impact on the environment is suspected.

As recommended by Palme et al. (2005), the social indicators regarding awareness and acceptance were represented by a percentage of users. Contrary to the finding of Rosemarin et al. (2012) regarding the unawareness of society about the environmental impact of the discharge of untreated wastewater to the recipient water, in both neighbourhoods, all interviewed inhabitants were stating to know about the negative impact. Most of them mentioned illness and infection as health risks and the contamination of the environment. Although, the credibility regarding the ladder may be questioned since few were able to mention examples for specific potential consequences.

It was found that a majority of the residents included in the survey were satisfied with the treatment systems. In both WWTPs, the associations place a high value on users' opinion. Regardless, many of them have complaints about the system and the event of returning wastewater from the sewerage system is, indeed, unacceptable.

All of the users were aware of that they are paying for the service. However, many did not know how high the tariff is. Of the few households knowing about the price, whether it was the one actually charged or not, only few stated the price to be too expensive. On average, half of all residents questioned were willing to pay more in case an enhancement of the system addresses the issues stated in their complaints. However, Fujita et al. (2005) experienced in Iquitos, Peru, that even if there is a WTP of the residents in developing countries for sanitation services, there is often a lack of affordability to pay (ATP). In those cases, it is a necessity to maximize the efficiency of O&M and to minimize costs where possible. Furthermore, Fujita et al. (2005) suggested increased development work in those regions to promote their economic growth and hence, increase the income of people what leads to a higher ATP.

Sato et al. (2013) criticised the lack of data records, as e.g. the national generated, treated and used amount of wastewater is often unknown or out-of-date. This problem was also encountered by Malik et al. (2015) who could not find data of the national connection level within Bolivia. Looking at the investigated WWTPs, the sewerage covers less than half, in El Paso, and little more than half of the households in San Pedro Magisterio. Even though this is a disappointing finding, the capacity of both WWTPs is great enough to connect all households and moreover, to cope with the wastewater flow of additional households.

The decreased negative impact of odour at the WWTP of San Pedro Magisterio may be explained by its location in a depression. As discovered by McKendry et al. (2002), the risk level of odour emission is highest if the source is located elevated, lowest when located on flat ground with protection from forests, and moderate if the WWTP is located in a valley. Of course, the direction of the wind and the temperature play a crucial role in the spreading of odour in an area, giving a clue why the complaints increase during warm days. In general, the buffer capacity in form of distance between houses and WWTP is a crucial factor to reduce the disturbance of the residents' everyday life. While the houses in El Paso are wider spread and the WWTP is located a bit outside of the dense part, in San Pedro Magisterio the housing area is relatively dense.

In South America, Cavallini and Young (2002) found that the treatment costs are often not considered in the service costs resulting in too low tariffs. As stated by the administrator of El Paso during one of the interviews, neither does the money collected through the fixed tariff for the sewage service covers for auto-sustaining the planta nor are their subsidies available. To overcome the deficit, the collected revenue for the drinking water services is used to pay for both services. This is a necessity also in reason of the construction of a new treatment unit. The same happens in San Pedro Magisterio where the price is a function of the consumed amount of drinking. Here, money is needed to buy more equipment and most urgently a mask for the operator to ensure safety at work.

With regard to the minimum wage (see Section 3.2.2), the operators at both WWTPs have very poor payment and work for less than what they have legally a right to, similarly, the secretary has a poor payment. In the other extreme, the hourly payment for the accountant more than four times the average at the WWTP of San Pedro Magisterio and its administrator gains more than double of the minimum wage per/hour. At El Paso, the payment distribution is more equal resulting in a lower average and hence, the disparity is reduced.

Challenges

Among other researchers, Malik et al. (2015) and Cavallini and Young (2002) found that in Latin America, the acquisition of data related to wastewater treatment is especially challenging which is a reason why rural areas are often left out in assessments due to barriers in the process of data collection. The same was encountered during this study and the amount of reliable data obtained was smaller than expected. Furthermore, there was a language barrier and there is an uncertainty of the answers were interpreted correctly; also, due to a lack of confidence in strangers and the missing expertise in executing surveys.

6.3 Comparison of the two WWTPs

The comparison of the WWTPs was done indicatively, as this was not the aim of the thesis. A more detailed would be necessary to fully and accurately compare the two WWTPs and clearly identify which is performing better. Here, the normalised values are discussed in terms of their accuracy in representing the real data. The simplified assignment of points does not reflect any range and must therefore be interpreted with caution since a slightly better performance for an indicator can lead to a WWTP being assigned one point. The comparison does therefore not reveal anything about how much better it is performing. In addition, the comparison is relative and does therefore not indicate if both WWTPs get poor results, e.g. at San Pedro Magisterio, the higher salary average per hour can actually not to be considered entirely positive due to unjust distribution among the employees.

Furthermore, the drastic step of valuing the missing of information as the worst possible outcome may be inadequate for some indicators. One case is the lack of laboratory analysis of the nitrogen removal at the WTTP of San Pedro Magisterio. It is unknown but might as well be lower than the extremely high effluent concentration found in El Paso. Another case may be that the data exist, but the person interviewed did not know about them. An Example can be given for the indicator *Chemicals consumed*, as the engineer at El Paso knew of the use of CaO and that the quantity is small, but because he did not know the exact amount and since there was no written information available at that moment, it was assigned the lowest score.

By making use of the ranks obtained to identify significant indicators within the set of SDIs, the perceived importance of local experts influenced the outcome of the final score. Even though the difference is small, it shows how easily the result can be shaped by small changes. In line with this, the low economic performance of the WWTP of San Pedro Magisterio was caused by the lack of information and hence, the strong weight placed on the availability of data over the entire comparison may affect the result significantly. Playing through the case that the lack of information within all sustainability aspects would have been assigned an equal score, the WWTP of San Pedro Magisterio would have received a higher score than the WWTP of El Paso. It is not a large difference; however, it demonstrates the sensitivity of such a simplified method.

6.4 Identification of significant SDIs in developing countries

The list of significant indicators contains five indicators that require special attention in developing countries. In a study conducted by Mahdi (2008), criteria were weighted by using the Saaty scale and for low-income groups, the capital and O&M costs received the highest importance. In accordance, the experts consulted in this work had the same opinion and rated *Operational cost* as the second and *Maintenance cost* as the fifth most significant indicator. The reliability of this outcome is supported by the influence diagram presented in Section 5.1.1 where the criterion "O&M costs" is identified as one of the ones having the highest influence on the system.

Contrary to Mahdi (2008), the amount of wastewater received and treated was considered as the third most significant indicator, while the quantity of generated wastewater in his study was perceived as an indicator of low importance. Another indicator identified as significant within this study was the *Complexity of the O&M*. As already discussed extensively within Section 6.2, those five indicators are indeed essential for achieving sustainability performance of small WWTPs in developing countries. However, the indicator receiving the highest rank amongst all was the *Availability of technical human resources* and is strongly interconnected to the complexity of the O&M.

Inferring from the indicators of lower importance, more indicators than it was done within this study could be eliminated from the set to perform the assessment. The *Property of land and fixed costs* was ranked lowest and its irrelevance may be perceived due to the two indicators of *Land cost* and the *Total area required* which already address the content of this indicator. For the same reason, the list of indicators perceived as less important may include many of the indicators addressing the removal efficiency of the WWTP within the technical dimension, since at the end, the effluent quality counts and the compliance with the standards are covered by indicators within the environmental dimension.

An interesting finding was that the institutional dimension was considered, among the experts, as the most important of the five dimensions and also includes the most and least significant indicators. In the influence diagram, these indicators only have few arrows, either receiving or leaving, but the five criteria address, directly or indirectly, the other four dimensions and among them, the ones described by the indicators identified as the most significant ones. The importance of the institutional capacity is pointed out by Massoud et al. (2009) who stated that it needs to be strengthened and changes in the administration must happen. The authority of the government must be substituted by local authorities (Sudasinghe, 2011) and the required bureaucratic procedure to enforce the realisation of projects must be reduced (Massoud et al., 2009). The involvement of the users should be pursued to ensure the sustainability of the sanitation system. Hence, by improving the institutional performance of a system, the performance of the other dimensions will increase.

The environmental dimension was considered the least important of the five dimensions. With regard to the influence diagram, the reason for this outcome can be explained by the weak effect the change of an environmental criterion has on the system. The highest importance within the environmental dimension, even though not a significant importance, was assigned to the indicator *Concentration of faecal coliforms in the effluent*. None of the significant indicators is an environmental or social indicator. On the other hand, of the sixteen indicators of lower importance, two are environmental and three are social indicators where the *Visual impact* received the second lowest rank of all. According to Andersson et al. (2016), adequate attention must be paid to social factors to make people change their habits and in agreement, in this study, the social dimension received the second highest number of points.

The reduction of the set must be considered, and one criterion, the “Level of interaction with users”, was perceived as less important and from the influence diagram it can be retrieved that it influences only one more indicator and is not influenced by any other criterion; hence, its elimination must be considered. The same is found for the indicators *Money available to reinvest, Buffer capacity, Buffer zone and Total area required.*
All indicators describing the criterion “Initial costs” are listed among the least important indicators. Their elimination, however, may be unwise due to its importance for a project’s enforcement in the first place. As it was no issue at neither of the two WWTPs, it is not surprising that the indicators *Visual impact* and *Noise emission* were ranked very low.
More difficult to interpret is the relevance of the criteria “Effluent quality” and “Removal Efficiency”. Many indicators within the ladder received low ranks; however, in the influence diagram the criterion is one of the main conjunction points of arrows while the “Effluent quality” and all its influences are dependent on the “Removal efficiency”. Considering that the desired removal efficiency is chosen according to the required effluent quality, instead of the efficiencies, the concentration in the effluent should be removed and only be used to determine the required efficiency by the treatment units. However, if an assessment takes place, it is the other way around and the criterion “Effluent quality” is of higher importance due to the negative impact of released contaminants on the environment but is directly influenced by the removal efficiency of constituents through the treatment process and hence, their functionality.

6.5 Limitations

So far, sets of SDIs were used as a tool to choose between alternatives of treatment technologies. Even though it is interconnected, the assessment of the entire WWTP must consider more but also different indicators to be meaningful in terms of the WWTP's sustainability. To use the set to investigate the two WWTPs in Bolivia, indicators were eliminated from the list in accordance with the recommendations given by experts familiar with wastewater treatment systems in Bolivia and ensuing, were validated. Nevertheless, the procedures of elimination and validation were very simplified compared to what was conducted in the study of Singhirunnusorn and Stenstrom (2009). For future use of the set of indicators, a ranking should be performed to validate the relevance of each indicator chosen and by the involvement of experts, aspects that were not addressed may be revealed and new indicators may be formulated and included in the set. Furthermore, for the assessment of the performance of already existing WWTPs, ranks could be used to give special importance to some indicators by multiplying the obtained and normalised data with the percentage received from the ranking.

A major limitation of this study is the high subjectivity of the results. Most data regarding the social impact were obtained through questionnaires at household level and as noted by Neuman (2004), the person's personal opinion directly influenced the outcome. Additional influence of subjectivity is generated by the process of ranking and rating (Molinos-Senante et al., 2014). Also, for the validation of indicators, there is an impact of subjectivity depending on personal opinion and expertise. Muga and Mihelcic (2008) identified that this bias results in different outcomes from one expert group to another. Besides a general overview of the project´s objective and the given conditions, a detailed clarification of all indicators, their meaning and impact, must be given to the participants.

The quantification of qualitative criteria by quantitative indicators is needed as described by Kalbar et al. (2013) but was not respected adequately in this study. Balkema et al. (2002) recommendeded to consider qualitative indicators even if not quantified to ensure the completeness of the assessment. The data regarding social indicators were obtained by conducting surveys in twenty different households which is, according to Neuman, (2004), a small scope for random sampling often fails to be representative.

From the perspective of Blancas et al. (2010), the approach of using a set of indicators comes along with the disadvantage of one indicator addressing the corresponding sustainability dimension. Based on this, Molinos-Senante et al. (2014) conducted a study on the assessment of a composite indicator representing global sustainability to provide a holistic sustainability assessment approach. However, it is challenging to assess this type of indicator and the robustness, which is a key characteristic of its meaningfulness, may result in being weak (Singh et al., 2012). The lack of data baulked the conduction of such an assessment and hindered the proper assessment of the sustainability of the two investigated WWTPs. Cossio et al. (2017) describe the unavailability of data as a major limitation in developing countries.

Due to a lack of records, data was given out of memory. During the surveys, it was possible to observe that some information was given with confidence but also that there was a high degree of insecurity in the answers to certain questions and those must be interpreted with caution. Additionally, and that might be related to many other factors, the reliability of the answers is suspected to be uncertain. In some cases, people seemed to answer what they thought was expected to be answered. For them, it is difficult to trust strangers and for most of the surveys, someone from the association whom the residents know was present. Several approaches could be used to overcome those limitations, as e.g. the recording of interviews and the subsequent interpretation with other experts, the clearer formulation of questions to yield for precise answers, the persistence to continue until the desired data is delivered, and the prosecution of data through various sources. All those suggestions a work-intense, require expertise and are time-consuming and were not realisable within the study.

7 Future practical application of SDIs

The set of sustainable indicators developed in this study was used to assess the sustainability of existing WWTPs but could also be implemented in the planning phase of new WTWTPs in developing countries to increase projects' success and ensure the sustainability performance of the WWTPs. Bakir (2001) describes the development of guidelines for selecting WWTSs for small communities as a considerable facilitation. This potential facilitation of the complexity of systems by the use of SDIs is according to Warhurst (2002) due to the resulting simplification, quantification, analysis and communication of information. The formulation of a guideline containing the SDIs according to the different phases during the planning and later during design and construction phase could help to make the entire process more effective, faster and hence, cheaper while securing the accomplishment of the formulated project's objective.

According to Bassan et al. (2014), through the validation of the set of SDIs before the start of a projects the understanding of all parties involved is increased in terms of the sustainable sanitation system's complexity. The participants learn about the various factors influencing the system and may have more positive responses to agree to compromises once they realise the importance of all aspects of sustainability. Depending on the goal of project and the local conditions, the perceived importance of each indicator may differ. Hence, the weighting can be used to consider those differences. This should be done through interviews in both cases: when assessing the sustainability of existing WWTPs and when planning new systems. The involvement of the administrative unit, the plant responsible, operators and engineers lead to a representative outcome. The list of indicators identified as most significant within this study should be included as mandatory in the guideline, but more studies are required to guarantee its completeness. The relevance of the other indicators must be evaluated with respect to the current project through ranking and rating. For this, an extensive assessment of the local conditions should be conducted to ensure that the right indicators are elected. Muga and Mihelcic (2008) stated that it is crucial to consider that each indicator should address the formulated goal, have a positive or negative impact, be unambiguously formulated, understandable and the set of indicators should be limited in number.

After this first step, Bassan et al. (2014) recommended the separation of the chosen indicators according to the stage they are relevant for, as e.g. planning, design or construction.
Moreover, for each indicator, the goal that is based on the project's purpose, stakeholders' interests, resources and legal requirements has to be assessed by the means of various tools like life cycle assessments (LCA), environmental impact assessment, risk assessments including microbial risk analysis, economic assessments, material flow analysis and uncertainty and sensitivity as well as investigations of acceptance and set of mindsets through interviews (Palme et al., 2005; Hellström et al.,

2000; Renou, 2008). For example, to reach the desired treatment efficiency, the treatment technologies must be chosen. This step could again be done by using another set of SDIs and performing a MCDA. With the help of literature studies, the expected investment costs can be calculated with cost functions after having decided which technologies to implement (Molinos-Senante et al., 2014). Cost-benefit analyses (CBAs) is an accepted and established tool used for decision-making purposes (Fan et al., 2013) and are described as "crucial" by the WHO (2012). Moreover, by knowing the incoming wastewater flow and the wastewater's constituents, the size of the future WWTP, the level of sophistication of the technologies and the resulting complexity of O&M can be estimated (Molinos-Senante et al., 2014). For social indicators, handbooks can be used, or surveys can be conducted. For environmental indicators, LCAs were found to produce valuable results for decision support (Corominas et al., 2013).

Following a guideline, WWTPs could be assessed with a standardised method, facilitating the comparison to other systems. Furthermore, and probably an even more important use may be the adoption of a guideline during the planning phase of a new WWTP in a developing country. By considering all the indicators relevant with respect to the local conditions, the chance of succeeding in the implementation of a sustainable performing WWTP can be increased. Additionally, the various points of perspectives included in the set of SDIs make the involved parties aware of the importance of other aspects and results in their collaboration rather than competition.

Despite the obvious potential benefits of a guideline that includes the use of SDIs, the application is connected to heavy workload since for the assessment of one single indicator several assessment tools may be needed (Molinos-Senante, 2014). The data acquisition to perform those assessments includes data from literature review, expert interviews and real data. The downside of indicators is that the indicators must be linked to a benchmark (Lancker and Nijkamp, 2000) and those benchmarks must be set for each WWTP depending on the objectives and the given conditions.

Recommendations based on previous studies

While a guideline may be applied for the assessment or the implementation of any small wastewater treatment system, in this section, the experiences from previous studies, conducted in developing countries and addressing various issues within the wastewater treatment sector, are shared to enhance and facilitate the development of such a guideline and increase its completeness. To achieve progress, it is essential to learn from both previous success and former failure.

A recommendation by Sudasinghe et al. (2011), after evaluating the performance of wastewater treatment systems in Sri Lanka, was the obligatory submission of annual reports to local authorities to keep track of the performance of the WWTP implemented.

Moreover, Sudasinghe et al. (2011) emphasize that the installation of a system itself does not come along with its success. This refers to what was reported by Bdour (2007):

When implementing new wastewater treatment technologies in developing countries, it is common to choose what has worked within the Western World. Unfortunately, there exist many examples of WWTPs failing due to this assumption, leading to the selection of inappropriate technologies. In the city of Amman, Jordan, a WWTP was donated consisting of an activated sludge system. Because the wastewater was not analysed beforehand, the high load with organics was unknown. The problems caused by this were tried to be fixed through other donations but turned out in making the situations worse. Kalbar et al. (2013) found that the error to exclude indicators addressing the location, social aspects and environmental impact led to resource wastage in India. According to Massoud et al. (2009), the reliance of developing countries on financial support from developed countries demands the donating countries to consider the local conditions when implementing a new WWTP in an unfamiliar terrain to ensure its sustainability. This is crucial to make maximal use from valuable investments.

Sperling and de Lemos Chernicharo (2002) were convinced that a stepwise implementation of treatment systems may often be the key to ensure the project's success. The first part to be implemented may not meet the requirements, but nevertheless, it will improve the situation compared to the discharge of untreated wastewater to the recipient water. Then, gradually the remaining parts can be implemented, and from stage to stage the treatment performance will until compiling with the required standard. This reduces the enormous financial pressure of implementing an entire system at once and prevents projects' from being postponed or even dropped. Despite the advantages, the challenge in developing countries is to ensure that the projects are pursued in the future.

Another finding by Massoud et al. (2009) was that decentralised wastewater must be considered as a sustainable solution for providing sanitation services to society in developing countries. The costs connected with centralised and mechanised WWTPs are often not affordable and their implementation is avoided, as it is the common case in Turkey (Engin and Demir, 2006). The concept of cluster systems as a type of decentralised wastewater system was promoted for developing countries due to its feasibility, flexibility, simpler maintenance and lower environmental impact by researchers as Engin and Demir (2006) and Libralato et al. (2012).

According to Hernandez-Sancho et al. (2011) and Singh and Kazmi (2018), the O&M costs have a considerable effect on the economic feasibility and the lifetime of WWTPs and must be included in the decision-making process when implementing a new system. Despite this finding, the costs for O&M can often not be covered by the charged service fees and at small WWTPs in Bolivia, the lack of O&M resulted in the poor performance of those WWTPs (Cossio et a., 2017). The main contributors to the operation costs are: the amount of wastewater to be treated, the topography of the location which may require pumps and the cost for energy, the wastewater constituents, the effluent quality standards, the sludge handling, the degree of automatization and hence, the cost for personnel and the plant's management (Wendland, 2005). In Guatemala, a WWTP was implemented through a donation from the European Union, but due to a lack of budget for O&M the project almost failed and additional effort was needed (Ratner and Rivera, 2004).

Muga and Mihelcic (2008) revealed that in developing countries, the technologies within a WWTP must be affordable and appropriate. Hence, less sophisticated systems are to be preferred (Sperling, 1996) to avoid additional financial strains on low-income populations. Moreover, they are more likely to succeed due to simpler O&M and additionally, offer reduced investment and O&M costs due to reduced energy consumption (Clarkson et al., 2010; Verbyla et al., 2013; Zhang et al., 2014) and in general require more employees and hence, decrease the unemployment rate (Muga and Mihelcic, 2008).

The nutrient removal from the wastewater demands more advanced technologies which cause an increase in both installation and O&M costs; hence, Verbyla et al. (2013) recommended to focus on nutrients recovery for the irrigational purpose. Then, the treatment should be located close to either the source or the place of reuse (Bakir, 2001). The importance of resource recovery does also apply for biogas which is produced during the anaerobic treatment of wastewater and provides the chance to generate energy that can reduce the operational costs and the direct use of it can compensate other costs (Verbyla et al., 2013). By Letting et al. (1993) those technologies are considered as the "sustainable solutions for environmental protection". For low-income countries, the UASB reactor is, according to Mahdi (2018), the best technology to be implemented if the TSS are sufficiently removed during post-treatment. In comparison with an activated sludge treatment, the investment cost of a UASB reactor in combination with a stabilization pond is half as expensive (Bdour, 2007).

Cavallini and Young (2002) reported the refusion of an activated sludge plant by the inhabitants of a neighbourhood in Cochabamba. A solution is the communication with the communities during the planning phase and surely before the implementation of any system to ensure its acceptance. Bdour (2007) noted that in projects within small communities, the involvement of local residents strengthens their belief and makes them confide in the system.

The missing awareness of the public regarding environmental and health impacts (Rosemarin et al, 2012), the limited effort in overcoming cultural barriers (Andersson et al., 2016), and the closeness to the treatment of human excreta are challenges of the implementation of decentralised wastewater treatment systems (DEWATS) and in some communities also other sanitation solutions (Ratner and Rivera, 2004). As mentioned previously, the education of the users regarding environmental and health impact facilitates the implementation of sustainable sanitation systems (Massoud et al., 2009).

Some indicators do not have a direct influence on the sustainability performance of a WWTP. For example, despite the lack of awareness, a WWTP can function sustainably. However, the awareness of the users is considered as necessary by Massoud et al. (2009) to achieve sustainable wastewater management in developing countries since it is closely related to the acceptance of the system. The awareness of the negative impact on health and environment makes people change habits (Munusmami et al., 2016) as experienced by Midkiff (2016) during her studies conducted in Peru, where many households dump other wastes in the toilets, resulting in problems within the sewerage system. Another effect of increased awareness could be the agreement to the implementation of a decentralised system and the enhancement of point-of source treatment. As a result, the treatment must remove fewer harmful substances and less sophisticated technologies are required. Furthermore, a study conducted by Munusmami et al. (2016) considered the possibility that the WTP may increase because people understand what they are supposed to pay for and their WTP is linked to the attitude towards the services. This may make the auto-sustaining of the WWTP possible if the tariff for the service is high enough to cover the O&M costs (Gallego Valero et al., 2018). Tram VO et al. (2014) revealed that besides the personal experiences, income and knowledge, the risk perception heavily impacts the WTP.

8 Conclusion

The amount of untreated wastewater discharged to the environment in developing countries is alarming. As a response, wastewater treatment systems are installed to cope with increased domestic wastewater, especially in the urbanising areas. However, those often fail in the long-term due to a lack of resources that result in poor planning and inadequate O&M, resulting in the failure of technologies and the violation of discharge limits. The identification of the cause of those failures was identified as a key to achieving the successful realisation of development projects for sustainable sanitation in developing countries. This should motivate to assess wastewater treatment systems and identify strengths and weaknesses regarding the aspects of sustainability as it was done for two WWTPs within this study by using a generated and validated set of SDIs.

The mayor challenge of applying the set of SDIs in the assessment of a WWTP was the consideration of many factors. It demands a structured approach to avoid errors and the involvement of many different parties makes it very complicated but at the same time brings many chances with it. The most positive one may be the understanding of the system by all stakeholders involved, resulting in enhanced communication.
The institutional dimension, which is often neglected, was identified to be of special importance within the set. Moreover, the most significant SDIs were identified to be the *Availability technical human resources, operational cost, amount of wastewater treated and received, complexity of O&M, maintenance cost.* Besides ranking, the design of influence diagrams is a useful tool to identify the importance of SDIs and their impact on others.

A general final conclusion drawn is that the support by developed countries is a necessity in developing countries and it is crucial to consider the local conditions to ensure the project´s success and to make each investment valuable.

Future research

The review of the set and the most significant indicators through a more detailed assessment and the design of influence diagrams for the indicators is recommended, because the methodology followed throughout this report was simplified. A major improvement to this study would be the implementation of MCA, including the assessment of indicators using tools like life cycle assessments, risk uncertainty assessments, cost-benefit analyses, and others. This refers to the selection of sustainability indicators for the general set as well as for the specified set of SDIs.
Moreover, the application of the generated set of SDIs was connected to difficulties during the acquisition and interpretation of the corresponding data. There is a great need for the setting of benchmarks to make the assessments meaningful, to facilitate their interpretation and to give clear orientation values to follow during the planning phase of projects.
For studies of a similar kind, it is recommended to ensure the collection of reliable data and to choose a larger scope for random sampling to make the outcome representative.

The application of the set of SDIs in further assessments of small wastewater treatment systems in developing countries will not only continuously improve the set but also provide example studies to learn from failures and successes. Furthermore, the application of the set in the planning phase is highly recommended to create a base for developing a simple guideline for implementing small wastewater treatment systems in developing countries and increase their long-term success.

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10 Appendices

10.1 Appendix A: Additional pictures of the two investigated treatment plants

WWTP of El Paso

Figure 50a: Screens, sedimentation channel and by-pass. Primary sludge was disposed in the circle of earth (lower right corner).

Figure 50b: UASB (on top) and gas burner (on bottom).

Figure 50c: Anaerobic filters. During dry days (on top) and during rainy days (on bottom).

Figure 50d: Maturation pond with plants growing extensively.

Figure 50e: Drying bed during rainy days.

Figure 50f: New treatment unit to improve the WWTP’s performance in construction.

WWTP of San Pedro Magisterio

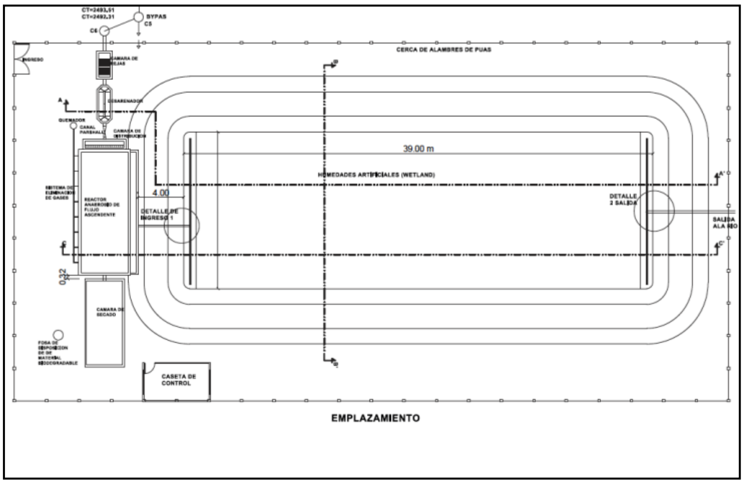


Figure 51a: Design plan of the WWTP San Pedro Magisterio. Source: Design drawings were provided by the Cooperativa de agua.

Figure 51b: Screens with added screen of smaller grit size mistakenly placed on first screen instead of second (on top) one, the sedimentation channels (on bottom left) and the Parshall channel (on bottom right).

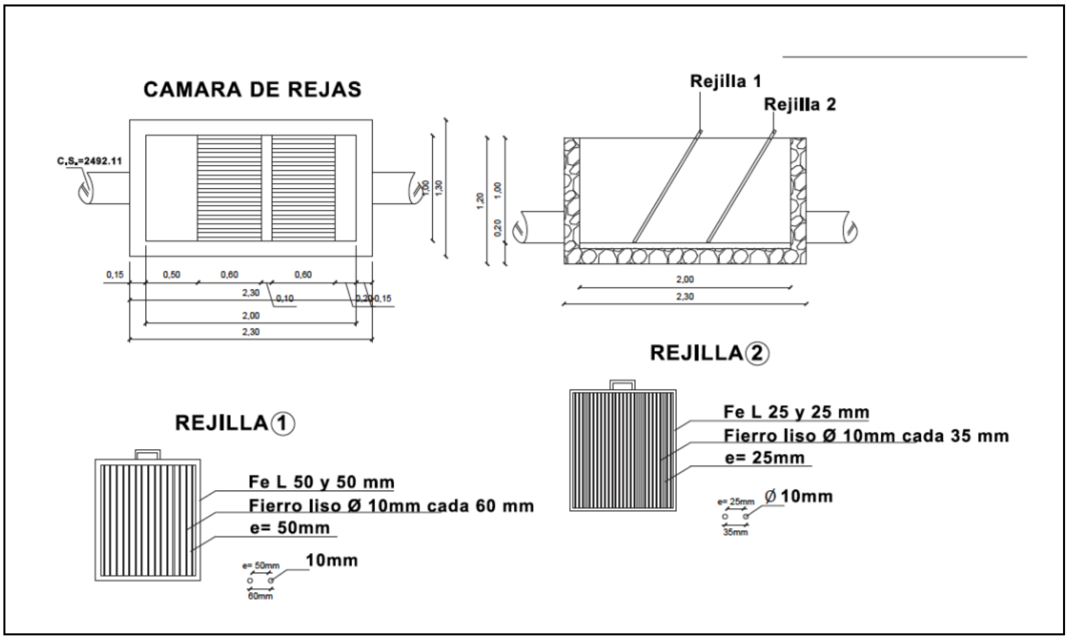


Figure 51c: Design of the screens implemented at the WWTP San Pedro Magisterio. *Source: Design drawings were provided by the Cooperativa de agua.*

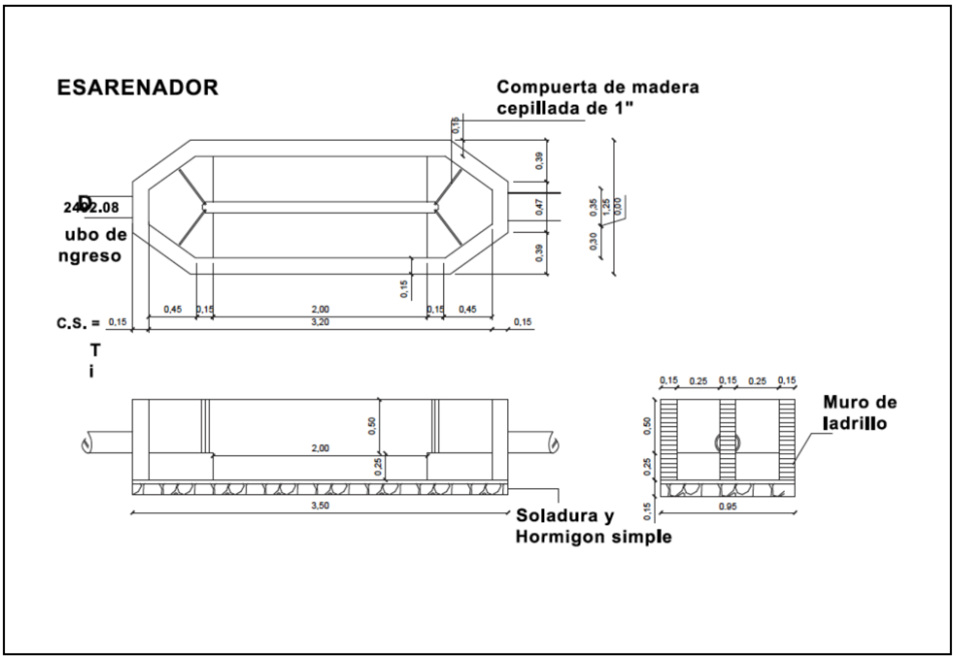


Figure 51d: Design of the sedimentation unit implemented at the WWTP San Pedro Magisterio. *Source: Design drawings were provided by the Cooperativa de agua.*

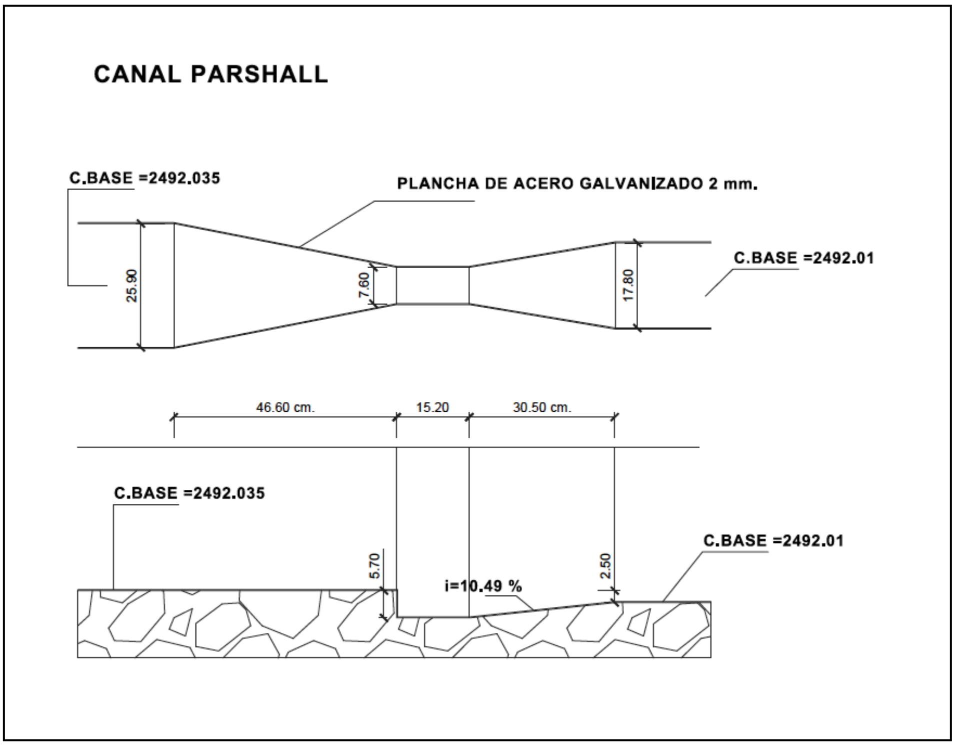


Figure 51e: Design of the Parshall channel implemented at the WWTP San Pedro Magisterio. *Source: Design drawings were provided by the Cooperativa de agua.*

Figure 51f: Pre-treatment units, distribution chamber of UASB and rests of the gas burner that was stolen at the beginning of this year.

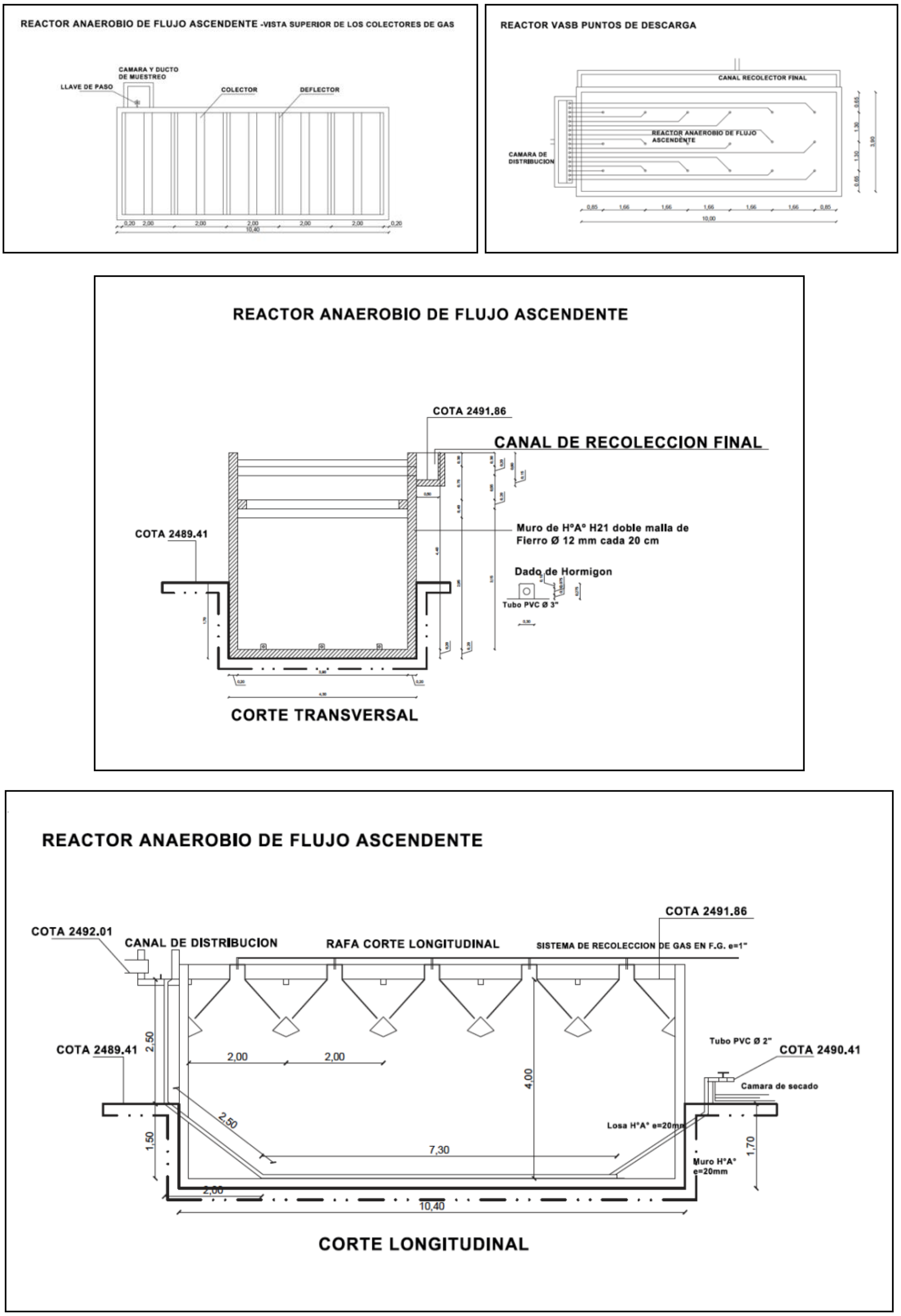


Figure 51g: Design of the UASB reactor implemented at the WWTP San Pedro Magisterio. On the top left, the reactor is shown with view from above, on the top right, the points of discharge to the reactor are drawn. In the middle, the cross-section is presented, and the bottom drawing shows the longitudinal section. *Source: Design drawings were provided by the Cooperativa de agua.*

Figure 51h: Inlet to the constructed wetland (on top) and constructed wetland (on bottom).

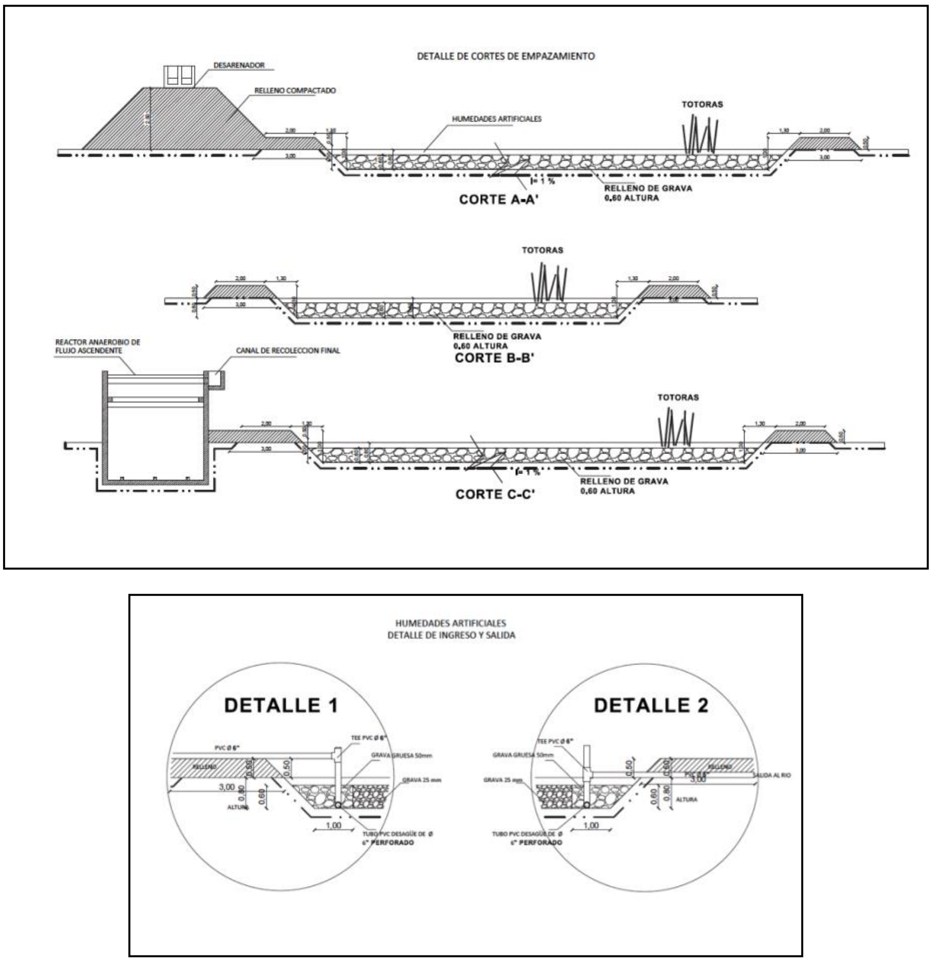


Figure 51i: Design of the biofilter implemented at the WWTP San Pedro Magisterio. *Source: Design drawings were provided by the Cooperativa de agua.*

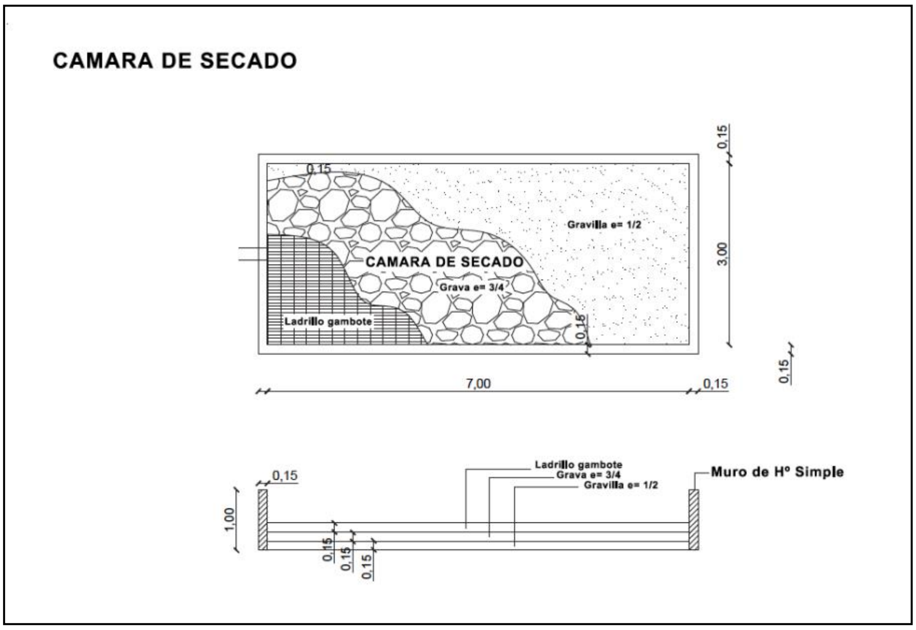


Figure 51j: Design of the drying bed implemented at the WWTP San Pedro Magisterio. *Source: Design drawings were provided by the Cooperativa de agua.*

Figure 51k: Outlet (on top) and vegetable garden, out of use, to reuse wastewater (on bottom).

10.2 Appendix B: Questionnaires

Technical unit

Questionnaire for the technical unit of the WWTP

Date: ___________ Name: ____

Cargo: ____ Age: ___________

Name of the treatment plant: ____

Name of the interviewer: ____

1) General data about the treatment facility

a) What type of organisation is in charge of the wastewater treatment plant (WWTP)?

Answer: ____

b) What is the total time that was required for the initial phase (planning, construction, installation, start-up)? **[years, months]**

Answer: ____

(1) In which year did the planning of the plant start? **[year-month-day]**

Answer: ____

(2) In which year did the construction start and when was it finished? **[year-month-day]**

Answer: ____

(3) In which year was the plant operated officially for the first time? **[year-month-day]**

Answer: ____

c) How much area in total is occupied by the treatment facility? **[m^2]**

Answer: ____

(1) What is the distance between the treatment plant and the closest houses? **[m]**

Answer: ____

(2) How much of the land is owned by the WWTP? **[m^2]**

Answer: ____

2) Operation and maintenance

a) Who is in charge of the operation of the plant? **[name]**

Answer: ____

b) Is there an operator employed?

Answer: ☐ yes ☐ no

- If the answer is yes:

  i) How often does he work? **[hours/week]**

  Answer: ____

  ii) What is the salary of the operator? **[US$ or Bs. /month]**

  Answer: ____

  iii) What are the main duties of the operator (e.g. cleaning of the units, regulation of the turbines, manage the flows, etc.)?

  Answer: ____

c) What are the activities of the operation that are conducted at the facility and with what frequency?

Answer: ____

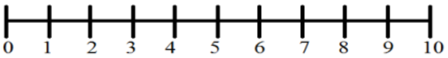
d) What are the activities of the maintenance that are conducted at the facility and with what frequency?

Answer: ____

e) Was the infrastructure within the design well-planned and well-constructed to facilitate the access during O&M?

Answer: ☐ yes ☐ no

[On a scale from 0 (does not apply) to 10 (applies to full extend)]



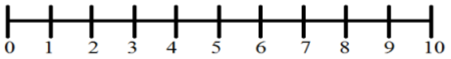
f) Do there exist plans for the infrastructure?

Answer: ☐ yes ☐ no

- If the answer is yes:

  i) What is the quality of these plans?

  Answer: **[On a scale from 0 (non-existent) to 10 (very detailed)]**



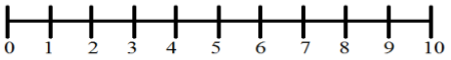
g) With what frequency does the plant require repairs? **[Ones per week; Once per month; Once per year]**

Answer: ____

h) Are operation and maintenance of the plant complicated?

Answer: ☐ yes ☐ no

[On a scale from 0 (simple) to 10 (extremely complicated)]



(1) Does there exist a manual for the operation and maintenance?

Answer: ☐ yes ☐ no

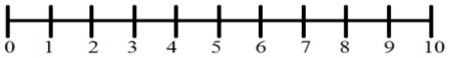
(2) What is the most complex unit to operate and maintain and why?

Answer: ____

i) Are there technical human resources available?

Answer: ☐ yes ☐ no

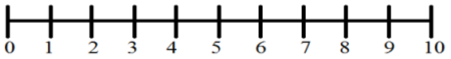
[On a scale from 0 (none) to 10 (all that are needed)]



j) Are there administrative human resources available?

Answer: ☐ yes ☐ no

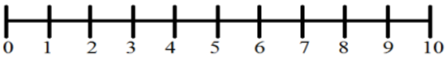
[On a scale from 0 (none) to 10 (all that are needed)]



k) Are there supplies and the equipment available?

Answer: ☐ yes ☐ no

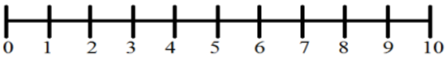
[On a scale from 0 (none) to 10 (all that are needed)]



l) Do there exist safety clothes?

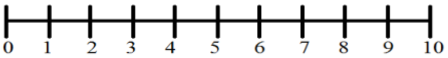
Answer: ☐ yes ☐ no

[On a scale from 0 (none) to 10 (all that are needed)]



m) What average level of education is required for the plant workers?

Answer: **[On a scale from 0 (no educational level) to 10 (expert educational level)]**



(1) Are there enough skilled personnel available at the treatment plant?

Answer: ☐ yes ☐ no

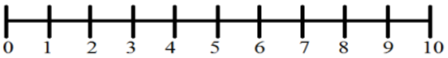
(2) Is there a need for the training of the employees?

Answer: ☐ yes ☐ no

- If the answer is yes:

  i) Do you have the means and the opportunity to attend and/or organise these trainings?

  Answer: **[On a scale from 0 (not possible) to 10 (realisable)]**



n) How much energy is consumed during the treatment process? **[kWh/m^3, kWh/month]**

Answer: ______________________________

(1) What is the monthly cost for energy? **[Bs. /month]**

Answer: ______________________________

o) What is the amount of fresh water consumed during the treatment process? **[L/m^3, L/month]**

Answer: ______________________________

(1) What is the monthly cost for the fresh water? **[Bs./month]**

Answer: ______________________________

p) What chemicals are used during the treatment process? **[names]**

Answer: ______________________________

(1) In what amount are these chemicals consumed during the treatment process? **[kg chemical/m^3, kg chemical/month]**

(2) What is the monthly cost for the chemicals? **[Bs. /month]**

Answer: ______________________________

q) What materials are consumed during the treatment process? **[names]**

Answer: ______________________________

(1) In what amount are these materials consumed during the treatment process? **[kg material/m^3, kg material/month]**

(2) What is the monthly cost for the materials? **[Bs. /month]**

Answer: ______________________________

3) Costs

a) How much money was invested during the process of construction (for start-up costs, material, equipment, machinery, working capital, design and other services)? **[US$ or Bs.]**

Answer: ______________________________

b) How much was the cost of the area of land required for the treatment plant? **[US$ or Bs.]**

Answer: ______________________________

c) Was the entire amount required for the initial phase contributed by the government?

Answer: ☐ yes ☐ no

- If the answer is no:
  - i) How much did they contribute? **[US$ or Bs.]**

    Answer: ______________________________
  - ii) Who else did contribute? **[names]**

    Answer: ______________________________

d) How many employees does the plant have? **[number]**

Answer: ______________________________

(1) What is their salary depending on their position (Operator, technical and unskilled staff)? **[Bs. /month; Bs. /year]**

Answer: ____

(2) How many hours does each of them work? **[hours/week]**

Answer: ____

e) How much money, in average, is spent per month for the maintenance? **[US$ or Bs. /month]**

Answer: ____

f) How much money, in average, is spent per month for the operation of the plant? **[US$ or Bs. /month]**

Answer: ____

g) Is there a budget available for unexpected costs as for substitution or repairs of technologies?

Answer: ☐ yes ☐ no

- If the answer yes:

i) How much money is available? **[US$ or Bs. /month]**

Answer: ____

h) How much money is available to cover costs for replacement or expansion in the future? **[US$ or Bs. /year]**

Answer: ____

i) How much money can the plant provide to sustain itself due to the incoming money from the users? **[US$ or Bs. /month]**

Answer: ____

4) Technical data and efficiency of the treatment plant

a) What are the treatment units and what technologies are used?

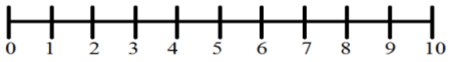
Answer: ____

(1) Are there plans for all implemented technologies available?

Answer: ☐ yes ☐ no

b) How complex was the construction of the treatment plant?

Answer: **[On a scale from 0 (simple) to 10 (extremely complicated)]**



(1) Who constructed the plant? **[name]**

Answer: ______________________________

c) For what wastewater flow was the plant designed? **[m^3/d]**

Answer: ______________________________

d) What wastewater flow is received and treated per day? **[m^3/d]**

Answer: ______________________________

(1) Do there exist plans for an expansion of the plant exist?

Answer: ☐ yes ☐ no

- If the answer is yes:

i) What is going to be implemented for expansion? Is the purpose the treatment of higher flows or the improvement of the effluent quality?

Answer: ______________________________

ii) With approximate assumptions, what do you think is the maximum capacity this plant can achieve after expansions? **[m^3/d]**

Answer: ______________________________

e) How high is the effluent flow discharged to the recipient water? **[m^3/d]**

Answer: ______________________________

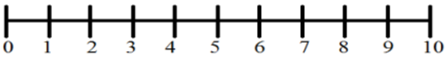
f) Are the influent and effluent flow recorded?

Answer: ☐ yes ☐ no

- If the answer is yes:

(1) How often are they recorded?

Answer: **[On a scale from 0 (never) to 10 (constantly)]**



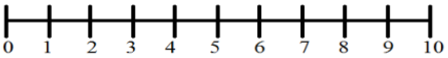
g) Have you analysed quality of the incoming wastewater?

Answer: ☐ yes ☐ no

- If the answer is yes:

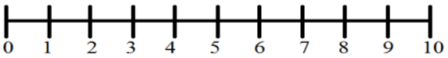
(1) How often is the water analysed?

Answer: **[On a scale from 0 (never) to 10 (regularly)]**



(2) Are the results recorded?

Answer: **[On a scale from 0 (never) to 10 (always)]**



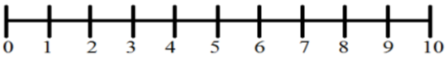
h) Have you analysed quality of the effluent?

Answer: ☐ yes ☐ no

- If the answer is yes:

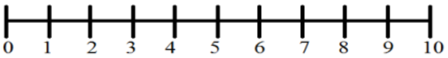
(1) How often is the water analysed?

Answer: **[On a scale from 0 (never) to 10 (regularly)]**



(2) Are the results recorded?

Answer: **[On a scale from 0 (never) to 10 (always)]**



5) Environmental aspects

a) Is sludge a by-product of the treatment process?

Answer: ☐ yes ☐ no

- If the answer is yes:

(1) How much sludge is produced per month? **[kg/m^3]**

Answer: ____

(2) How is the sludge handled? **[process]**

Answer: ____

(3) Is there a reuse of the treated sludge?

Answer: ☐ yes ☐ no

- If the answer is yes:

(a) For what is the sludge reused? **[purpose]**

Answer: ____

- If the answer is no:

(b) Is there interest or future potential to reuse it?

Answer: ☐ yes ☐ no

b) Is methane a by-product of the treatment process?

Answer: ☐ yes ☐ no

- If the answer is yes:

(1) How is the is methane handled? **[process]**

Answer: ____

(2) Is there a reuse of the gas?

Answer: ☐ yes ☐ no

- If the answer is yes:

(a) For what is the gas reused? **[purpose]**

Answer: ____

- If the answer is no:

(b) Is there interest or future potential to reuse it?

Answer: ☐ yes ☐ no

c) Is the treated effluent water reused?

Answer: ☐ yes ☐ no

- If the answer is yes:

(a) For what is the water reused? **[purpose]**

Answer: ____

○ If used for irrigational purpose:

(i) What types of cultivations?

Answer: ____

(b) How far downstream from the point of discharge is the water reused? **[m]**

Answer: ____

- If the answer is no:

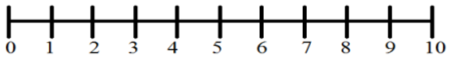
(c) Is there potential to reuse it?

Answer: ☐ yes ☐ no

(1) Are you aware of the benefits of using treated wastewater?

Answer: ☐ yes ☐ no

[On a scale from 0 (not aware) to 10 (extremely aware)]



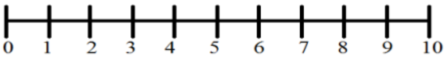
(a) What are the benefits you are aware of?

Answer: ____

(2) Are you aware of the risk of using for the reuse insufficient treated wastewater?

Answer: ☐ yes ☐ no

[On a scale from 0 (not aware) to 10 (extremely aware)]



(a) What are the risks you are aware of?

Answer: ____

(b) Are there cases known, where children or farmers were affected using the treated wastewater?

Answer: ☐ yes ☐ no

- If the answer is yes:

  (i) Did this happen in the last 5 years?

  Answer: ☐ yes ☐ no

d) Are nutrients as phosphorus and nitrogen recovered from the wastewater?

Answer: ☐ yes ☐ no

- If yes:

  (a) In what amount is … recovered? **[mg/L]**

    a. Phosphorus

    Answer: ____________________________________

    b. Nitrogen

    Answer: ____________________________________

e) Where is the point of discharge of the effluent located and what rivers does it influence downstream? **[location; name of rivers]**

Answer: ____

f) Does it occur that wastewater is released untreated or insufficiently treated to the recipient water?

Answer: ☐ yes ☐ no

- If the answer is yes:

  (a) During what types of events is the wastewater not treated as under normal operation?

  Answer: ____

  (b) How often is the treatment shut down and how often is it reduced during the period of a year and in what season of the year?

  Answer: ____

6) The users of the system

a) For approximately how many users is the plant constructed? **[pe or households]**

Answer: ____

(1) How many users are connected to the wastewater treatment plant? **[pe or households]]**

Answer: ____

(2) How many users in the district are still not connected to the sewage system?? **[pe or households]**

Answer: ____

(3) How many users are connected to the water system? **[pe or households]**

Answer: ____

b) Does there exist a tariff for the users connected to the wastewater treatment plant?

Answer: ☐ yes ☐ no

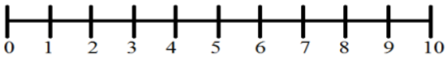
- If the answer is yes:

(a) What is the tariff per m^3 and person? **[Bs/m^3]**

Answer: ____

(b) As how appropriate do you judge this tariff?

Answer: **[On a scale from 0 (not appropriate) to 10 (very appropriate)]**



c) Are there events to communicate with the users of the system?

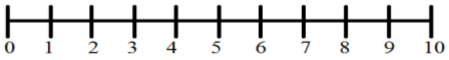
Answer: ☐ yes ☐ no

- If the answer is yes:

(a) How often do these events occur? **[number]**

Answer: ____

[On a scale from 0 (never) to 10 (very regularly)]



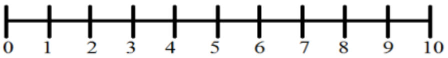
(2) Are the reports with the users recorded?

Answer: ☐ yes ☐ no

- If the answer is yes:

(a) How many are recorded?

Answer: **[On a scale from 0 (none) to 10 (all)]**



Users

Questionnaire for the users of the sewage system

Date: ___________________ Place-Neighbourhood: ____________________________________

Name: ____ Age: _________________

Cargo: ____

Name of the interviewer: ____

1) General data

a) How many people are living in the household? **[number]**

Answer: ____

b) Do you receive potable water from the system?

Answer: ☐ yes ☐ no

- If the source is the public drinking water system:

(1) How much water do you consume per month? **[L or m^3]**

Answer: ____

(2) For what do you use the water? **(Bathing, Showering, Washing the clothes, Cooking, Irrigation, etc.)**

Answer: ____

(3) Do you receive a sufficient amount of water?

Answer: ☐ yes ☐ no

(4) How much do you pay for the water per month? **[Bs/month]**

Answer: ____

2) Health

a) Do you think it is necessary to have a wastewater treatment system to protect the human health?

Answer: ☐ yes ☐ no

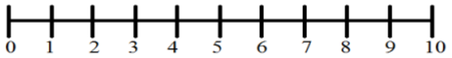
b) Have you ever experienced illness that you related to the insufficient quality of the wastewater released by the treatment plant (e.g. through food or when using the water for other purposes)?

Answer: ☐ yes ☐ no

- If the answer is yes:

  i) How often was this the case?

  Answer: **[On a scale from 0 (never) to 10 (regularly)]**



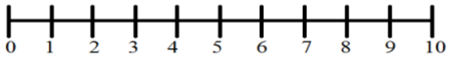
3) Environment

a) Do you think it is necessary to have a wastewater treatment system to protect the environment?

Answer: ☐ yes ☐ no

b) Are you aware of the consequences of releasing untreated wastewater to the environment?

Answer: **[On a scale from 0 (not aware) to 10 (extremely aware)]**



(1) What do you think are the most significant impacts and how do they affect the environment and the people living there?

Answer: ____

4) The wastewater treatment facility

a) Are you connected to the sewage system?

Answer: ☐ yes ☐ no

- If the answer is yes:

(1) Which facilities **(kitchen, bathroom, washing machine)** in your household are connected?

Answer: ____

b) Are you satisfied with the wastewater treatment system?

Answer: ☐ yes ☐ no

- If the answer is no:

(1) Do you have complaints about the system?

Answer: ☐ yes ☐ no

- ○ If the answer is yes:

(a) What are these complaints about?

Answer: ____

(b) Do you think there should be any improvements of the system?

Answer: ☐ yes ☐ no

- ▪ If the answer is yes:

(i) What improvements do you suggest?

Answer: ____

c) Do you pay for the treatment of the wastewater?

Answer: ☐ yes ☐ no

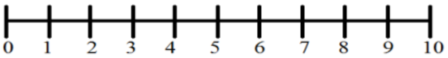
- If your answer is yes:

i) How much do you pay? **[Bolivianos/month]**

Answer: ____

ii) What is your opinion about the price?

Answer: **[On a scale from 0 (extremely low) to 10 (extremely high)]**



(a) In case of the improvement or expansion of the system, would you be willing to pay a higher tariff?

Answer: ☐ yes ☐ no

d) Do you know the wastewater treatment plant?

Answer: ☐ yes ☐ no

- If the answer is yes:

(1) Do you accept the wastewater treatment plant?

Answer: ____

(2) Do you know where the treated wastewater ends up?

Answer: ☐ yes ☐ no

- ○ If the answer is yes:

i) Do you know if there are families or farmers who use this water?

Answer: ☐ yes ☐ no

- ▪ If the answer is yes:

(a) Do you know for what purpose they use it?

Answer: ____

(b) Do you know if the reuse caused any problems?

Answer: ____

5) Impact on the everyday life

a) Does the plant emit odour?

Answer: ☐ yes ☐ no

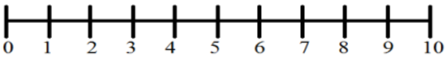
- If your answer is yes:

(1) Do you feel personally disturbed by this odour in your everyday life?

Answer: ☐ yes ☐ no

(2) How often do you feel disturbed?

Answer: **[On a scale from 0 (never) to 10 (always)]**



b) Are noises produced by the plant?

Answer: ☐ yes ☐ no

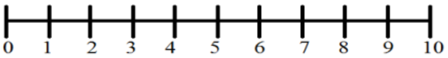
- If your answer is yes:

(1) Do you feel personally disturbed by these noises in your everyday life?

Answer: ☐ yes ☐ no

(2) How often do you feel disturbed?

Answer: **[On a scale from 0 (never) to 10 (always)]**



c) Does the visual appearance of the plant affect the landscape?

Answer: ☐ yes ☐ no

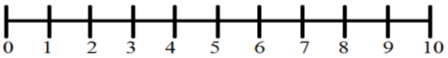
- If your answer is yes:

(1) Do you feel personally disturbed by this visual impact in your everyday life?

Answer: ☐ yes ☐ no

(2) How often do you feel disturbed?

Answer: **[On a scale from 0 (never) to 10 (always)]**



Questionnaire for the laboratory at CASA

How high is the concentration of	**[Unit]**	**In the influent?**	**After the pre-treatment?**	**In the effluent?**
Oil and greases	[mg/L]			
TSS	[mg TSS/L]			
COD	[mg O_2/L]			
BOD	[mg O_2/L]			
Faecal coliforms	[UFC/ 100 mL]			
Total N	[mg N/L]			
Total P	[mg P/L]			

10.3 Appendix C: Data obtained at the two WWTPs

Table 11: The obtained answers regarding the economic aspect for both treatment plants: El Paso (EP) and San Pedro Magisterio (SPM).

Economic Indicator	Question	[Unit]	EP	SPM
Construction cost	*How much money was spent during the process of construction? For start-up costs, material, equipment, machinery, working capital, design and other services?*	[US-$]	202678	60000
Land cost	*How much did the area cost the treatment plant is built on or if provided by the government, how much would it have been worth when sold to use as agricultural or industrial land?*	[-]	0; worth 46 000	Provided by the community (OTB).
Cost subsidy from government	*How much money was provided by the government?*	[US-$]	86862	0
	How much was provided by other operators?	[US-$]	115816	0; The money was provided through donation of NGO and Foundation "Abril".
Operational cost	*How much energy is consumed?*	[kWh/month]	0	0
	How much money is required to cover the energy demand of the plant?	[US-$/month]	0	0
	What chemicals are used in the treatment process?	[-]	None	None
	In what amount?	[kWh/month]	0	0
	How much money is spent on them?	[US-$/month]	0	0

	What materials are consumed?	[-]	Sand, painting colour, gravel	Sand, gravel, painting colour, wire mesh.
	In what amount?	[kWh/month]	No information available.	No information available.
	How much money is required?	[US-$/month]	No information available.	8,5
Administration cost	*How many people are working at the plant?*	[-]	3	5
	What are the salaries of scientific, technical and unskilled staff?	[US-$/month]	Total - 1072 Operator - 348 Secretary - 290 Plumber 434	Total - 1303 Operator - 290 Secretary - 304 Administrator - 333 Plumber - 304 Accountant - 72
	What are the costs for pension and insurance per worker?	[US-$/month]	0	0
Maintenance cost	*How much money is spent in the maintenance and operation of the plant?*	[US-$/month]	965	No information available.
Budget for unexpected cost	*How much budget is considered for emergency cases as e.g. the failure of a treatment technology?*	[US-$]	0	No information available.
Capacity for re-investment	*How much money is available to reinvest in the plant for replacements or expansions?*	[US-$]	0	No information available.

Table 12: The obtained answers regarding the technical aspect for both treatment plants: El Paso (EP) and San Pedro Magisterio (SPM).

Technical Indicator	Question	[Unit]	EP	SPM
Amount of wastewater received and treated	*What is the wastewater flow the treatment plant was designed for?*	[L/s]	10	3,6
	How high is the incoming wastewater flow to the treatment plant?	[L/s]	2,8	1,11
Removal efficiency of oil and grease	*How high is the incoming concentration?*	[mg/L]	74	22
	What concentration is found in the effluent of the pre-treatment section?	[mg/L]	41,5	3
	What is the percentage of removal?	% of removal	43,92	86,36
Removal efficiency of Total Suspended Solids (TSS) in the pre-treatment	*How high is the incoming concentration?*	[mg SS/L]	No information available.	No information available.
	What concentration is found in the effluent of the pre-treatment section?	[mgSS/L]	No information available.	No information available.
	What is the percentage of removal?	% of removal	No information available.	No information available.
Removal efficiency of TSS	*How high is the incoming concentration?*	[mg SS/L]	347,5	348
	What concentration is found in the effluent of the treatment section?	[mg SS/L]	71	82
	What is the percentage of removal?	% of removal	79,57	76,44
Removal efficiency of Chemical Oxygen Demand (COD)	*How high is the incoming concentration?*	[mg O2/L]	652,5	588
	What concentration is found in the effluent of the treatment section?	[mg O2/L]	253,5	123
	What is the percentage of removal?	% of removal	61,15	79,08

Removal efficiency of Biological Oxygen Demand (BOD)	*How high is the incoming concentration?*	[mg O2/L]	210	361
	What concentration is found in the effluent of the treatment section?	[mg O2/L]	168	82
	What is the percentage of removal?	% of removal	20,00	77,29
Removal efficiency of Faecal Coliforms (FC)	*How high is the incoming concentration?*	[UFC/100mL]	3,57E+07	4,80E+07
	What concentration is found in the effluent of the treatment section?	[UFC/100mL]	3,53E+06	1,00E+07
	What is the percentage of removal?	% of removal	90,09	79,17
Removal efficiency of Total Nitrogen	*How high is the incoming concentration?*	[mg N/L]	123,25	No information available.
	What concentration is found in the effluent of the pre-treatment section?	[mg N/L]	116,78	No information available.
	What is the percentage of removal?	% of removal	5,25	No information available.
Removal efficiency of Phosphorus	*How high is the incoming concentration?*	[mg P/L]	15,86	18,67
	What concentration is found in the effluent of the pre-treatment section?	[mg P/L]	17,7	11,02
	What is the percentage of removal?	% of removal	-11,60	40,97
Complexity of initial phase	*How complicated was the construction, installation and starting of the system?*	[-]; 0 simple - 10 extremely complicated	No information available.	Construction was simple; 1
	Where there many engineers, architects and experts required?	[-]	No information available.	No information available.

Accessibility provided through infrastructure for O&M	*Was the infrastructure of the plant well-constructed to facilitate the access for O&M?*	Yes or no; 0 does not apply - 10 applies to full extent	Yes; 10 (operator), 6 (administrator); No; 7 (engineer)	Yes; 5
Time required for the initial phase	*How long did the planning, the construction, the installation and the starting of the system take? (from planning to first day of operation)*	[years]	9	1
Complexity of O&M	*How complex is the operation and maintenance of the plant?*	0 simple to - 10 extremely complicated	Yes; 9 (operator), 5 (administrator), 7 (engineer)	7
	What is the most complicated unit?	[-]	Cleaning of the UASB reactor	Cleaning of the screens and the sedimentation channel.
	Does there exist a manual for the O&M?	Yes or no	No	No
Requirement of skilled staff	*What level of education of the plant workers is required?*	[-]	Highschool degree	Operator has a high school degree.
	Is there enough skilled staff employed?	[-]	No, permanent engineer required.	Yes, when including the volunteer engineer.
Requirement of training for staff	*Is there a need to train the staff?*	[-]	Yes, to improve the institution.	No need, engineer trains the others.
Buffer capacity	*How much more wastewater could be treated?*	[l/s]	7,2	2,49
	How many more households could be connected?	[-]	1373	672

Table 13: The obtained answers regarding the environmental aspect for both treatment plants: El Paso (EP) and San Pedro Magisterio (SPM).

Environmental Indicator	Question	[Unit]	EP	SPM
Nutrients recovery	*How much phosphorus is recovered?*	[mg P/L]	0	0
	How much nitrogen is recovered?	[mg N/L]	0	0
Sludge reuse	*Is sludge produced during the treatment process?*	yes or no	Yes	No
	How much sludge is produced?	[kg Sludge/m^3 WW]	wet: 90; dry: 30	0
	Of what does the treatment of the sludge consist?	[-]	Drying beds, Disposal	-
	In case of reuse, how much sludge is reused?	[kg sludge/ month]	No reuse.	No reuse.
	For what is the sludge reused?	[-]	-	-
Methane reuse	*Is methane produced during the treatment process?*	yes or no	Yes	Yes
	How much methane is produced?	[kg CH4/m^3 WW]	No information available.	Small quantity
	How is the methane handled?	[-]	Burned	It is burned.
	In case of reuse, how much methane reused?	[kg CH4/month]	No reuse.	No reuse.
	For what is the methane reused?	[-]	-	-
Water reuse	*Is the treated wastewater from the wastewater treatment plant reused?*	yes or no	Yes, by some neighbours.	Yes
	How much of the wastewater is reused?	[m^3 WW reused/m^3 effluent]	No information available.	No information available.

	For what is the wastewater reused?	[-]	For irrigational purpose.	For irrigational purpose.
Amount of fresh water consumed	*What is the total amount of fresh water consumed for the treatment process?*	[m^3 fresh water/m^3 WW]	0	0
Chemicals consumed	*What chemicals are used during the treatment?*	[-]	CaO	None
	In what quantity are they consumed?	[kg chemical/m^3 WW]	No information available.	0
Materials consumed	*What materials are used during the treatment?*	[-]	0	0
	In what quantity are they consumed?	[kg material/m^3 WW]	0	0
Energy consumed	*How much energy is consumed during the treatment process?*	[kWh/m^3 WW]	0	0
TSS in effluent	*How high is the conc. of TSS in the effluent?*	[mg/L]	71	82
COD in effluent	*How high is the conc. of COD in the effluent?*	[mg O2/L]	253,5	123
BOD in effluent	*How high is the conc. of BOD in the effluent?*	[mg O2/L]	168	82
FC in effluent	*How high is the conc. of FC in the effluent?*	[UFC/100 mL]	3,53E+06	1,00E+07
TN in effluent	*How high is the conc. of TN in the effluent?*	[mg N/L]	116,78	No information available.
P in effluent	*How high is the conc. of P in the effluent?*	[mg P/L]	17,7	11,02
Total area required	*How much area is occupied by the facility?*	[m^2]	2 947	1 493
Area of buffer zone	*What is the distance between the plant and the closest house?*	[m]	50	100

Table 14: The obtained answers regarding the social aspect for both treatment plants: El Paso (EP) and San Pedro Magisterio (SPM).

Social Indicator	Question	[Unit]	EP	SPM
Health impact	*How many people consider the treatment of the wastewater necessary to protect human health?*	[% of people questioned]	100	100
	How many do know cases where people got ill, and the quality of water was suspected a cause?	[% of people questioned]	10	5
Environmental impact	*How many people consider the treatment of the wastewater necessary to protect the environment?*	[% of people questioned]	100	100
	Are they aware of the impact of untreated wastewater released to the environment?	[% of people questioned]	70	65
	What type of impacts are known?	[-] ([%])	Contamination of the environment (36,71), Infections/Illness (71,41), Odour (28,57)	Contamination of the environment (38,46), Infections/illness (85,62), Mosquitos (7,69)
Satisfaction with sewage system	*How many people are satisfied with the system?*	[% of people questioned]	80	70
	How many people have complaints about the treatment systems?	[% of people questioned]	10	65
	What kind of complaints?	[-] ([%])	WW returns in times of heavy rain (100)	WW returns from the canalisation system (85,72), Odour (14,28 %)

	How many people expressed the need for improvement of the system?	[% of people questioned]	35	55
	What type of improvement?	[-] ([%])	Connect all households (57,14), Change of pipes to prevent returning of WW (28,57)	Change of pipes to prevent returning of WW (72,73), Higher purification (18,18)
% of sewage covergae	*How many households have access to improved sanitation with the connection to the wastewater treatment facility?*	[% of people questioned]	85	100
	How many households are connected to the wastewater treatment facility?	[-]	534	1500
	What is the total number of households in the district of the wastewater treatment plant?	[-]	1200	2680
	What is the coverage of households with connection to the sewage system?	[%] = Households connected/Households total	44,5	56
Willingness to pay a fair tariff for collection and treatment	*Is there a tariff charged for the collection and treatment of the wastewater?*	Yes or no	Yes	Yes
	How many do know that they pay?	[% of people questioned]	65	95
	How high is the tariff (average price paid)?	[Bs./month]	5	9,81; real price is 1,1

	Is the tariff perceived as justified?	Yes or no	Yes (5), Too cheap (11,11), Too expensive (11,11)	Yes (100)
	In case of improvement, is there a willingness to pay more for the service?	Yes or no ([% of people questioned])	Yes (45)	Yes (55)
Odour	*Is odour emitted from the treatment facility?*	Yes or no ([% of people questioned])	Yes (50)	Yes (45)
	Is the odour considered as disturbing in the everyday life?	Yes or no ([% of people questioned])	Yes (30)	Yes (100)
	How often is this the case?	[-] ([% of people questioned])	Very often (8,67) - during the night and in the morning	When it is hot (44,44), In the mornings (11,11)
Noise	*Are there noises emitted from the treatment facility?*	Yes or no ([% of people questioned])	No (100)	No (100)
	Is the noise caused by the treatment plant itself and related traffic considered as disturbing in the everyday life?	Yes or no ([% of people questioned])	-	No (100)
	How often is this the case?	[-]	-	-
Visual impact	*Does the facility have a visual impact?*	Yes or no ([% of people questioned])	Yes (30)	Yes (20)
	Is it considered as disturbing in everyday life?	Yes or no ([% of people questioned])	No information available.	No (100)
	How often is this the case?	[-]	No information available.	No information available.

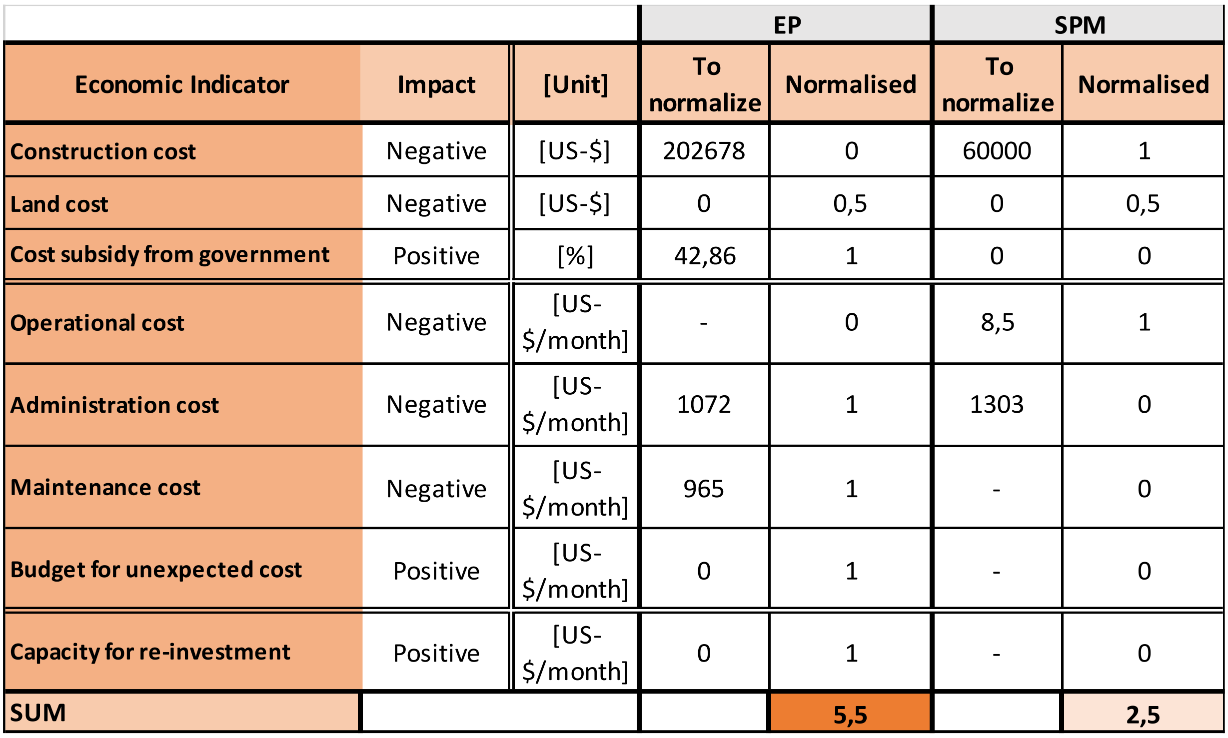
Table 15: The obtained answers regarding the institutional aspect for both treatment plants: El Paso (EP) and San Pedro Magisterio (SPM).

Institutional Indicator	Question	[Unit]	EP	SPM
Available technical human resources	*Are there enough technical human resources?*	Yes or no	Yes	Yes
Available administrative resources	*Are there enough administrative human resources?*	Yes or no	Yes	Yes
Available supplies and equipment	Are there enough supplies and equipment?	Yes or no	Yes	Yes
Record of flows	*Are the flows recorded constantly over a sufficient span of time?*	Yes or no	No	No
Record of analysis of the quality of wastewater	*Are there analyses of the wastewater quality (both influent and effluent) recorded?*	Yes or no	Yes, conducted engineer.	Yes, conducted by university.
	With what frequency?	[per year]	Once per year	Once per year
Plans of the infrastructure	*Do plans for the infrastructure exist?*	Yes or no	Yes	Yes
Number of communication events with users	*Are there events to communicate with the users of the system?*	Yes or no	Yes	Yes
	How often are these conducted?	[per year]	Once per year	Once per year
Number of annual socialized reports with users	*How many reports with the users are recorded?*	[-]	All	All

Level of salary	*What is the salary of the employees (related to their position in the plant?*	[US-$/hour]	Operator - 1,55 Secretary - 1,81 Plumber 2,72	Operator - 1,65 Secretary - 2,04 Administrator - 4,16 Plumber - 3,04 Accountant - 9,05
Safety conditions	*Are there safety clothes available at the plant and is that enough?*	Yes or no	Yes	No, mask for operator is missing
Property of land and fixed activities	*How much of the land is owned by the treatment plant?*	[%] = m^2 property/m^2 total	100	100
Auto-sustainable financing (own means)	*What is the amount of money that the plant can provide?*	[US-$/month]	Self-sustaining with tariffs for drinking water service	No information available.

10.4 Appendix D: Distribution of points for comparison of the WWTPs

Table 16: Direct comparison within the economic dimension by assigning points of 0, 0,5 or 1 to the WWTPs for each indicator.

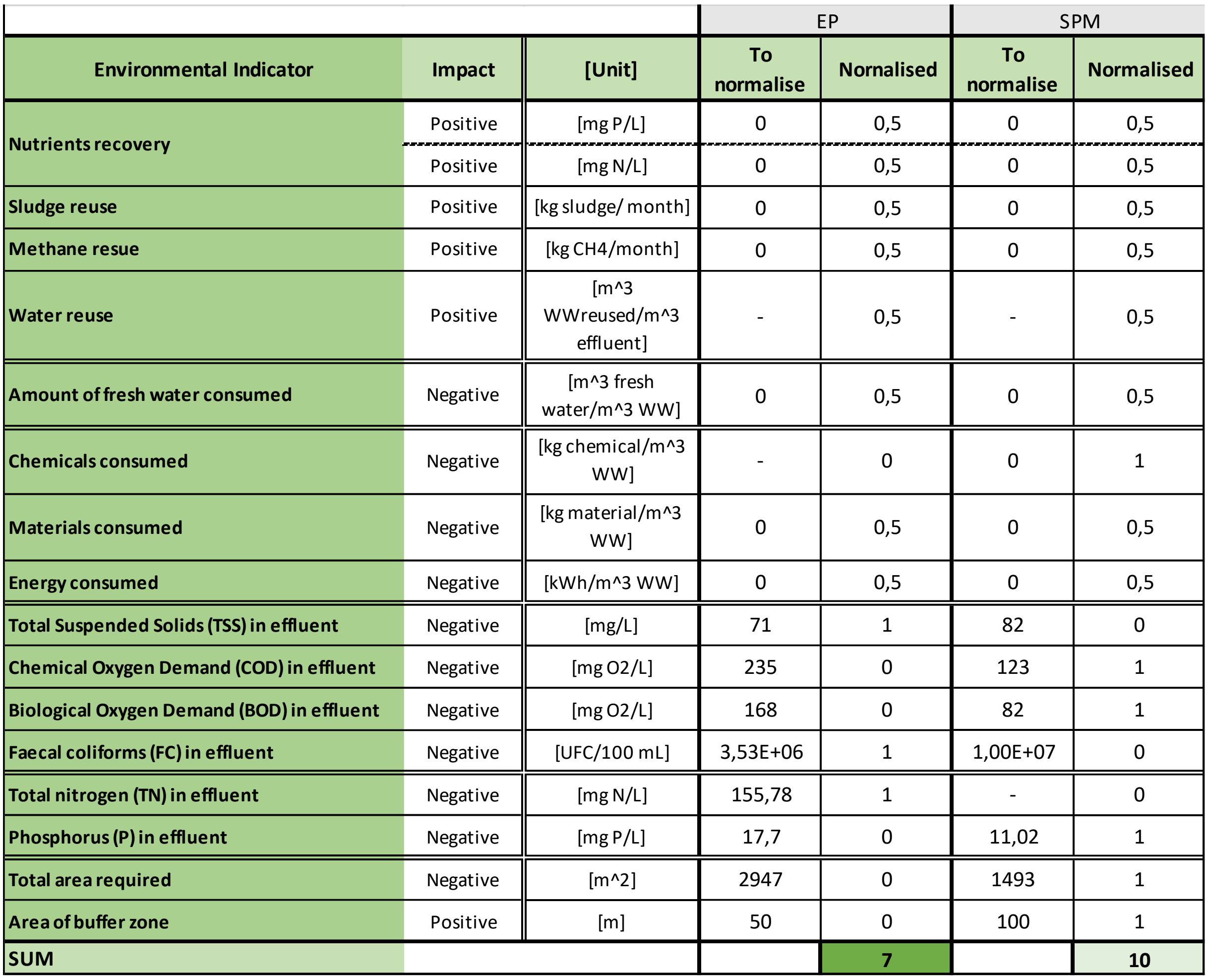


			EP		SPM	
Economic Indicator	**Impact**	**[Unit]**	**To normalize**	**Normalised**	**To normalize**	**Normalised**
Construction cost	Negative	[US-$]	202678	0	60000	1
Land cost	Negative	[US-$]	0	0,5	0	0,5
Cost subsidy from government	Positive	[%]	42,86	1	0	0
Operational cost	Negative	[US-$/month]	-	0	8,5	1
Administration cost	Negative	[US-$/month]	1072	1	1303	0
Maintenance cost	Negative	[US-$/month]	965	1	-	0
Budget for unexpected cost	Positive	[US-$/month]	0	1	-	0
Capacity for re-investment	Positive	[US-$/month]	0	1	-	0
SUM				**5,5**		**2,5**

Table 17: Direct comparison within the technical dimension by assigning points of 0, 0,5 or 1 to the WWTPs for each indicator.

			EP		SPM	
Technical Indicator	**Impact**	**[Unit]**	To normalise	Nornalised	To normalise	Normalised
Amount of wastewater received and treated	Neutral	[l/s] [l/s]	10 2,8	0,5	3,6 1,11	0,5
Removal efficiency of oil and grease	Positive	% of removal	43,92	0	86,36	1
Removal efficiency of Total Suspended Solids (TSS) in the pre-treatment	Positive	% of removal	-	0,5	-	0,5
Removal efficiency of TSS	Positive	% of removal	79,57	1	76,44	0
Removal efficiency of Chemical Oxygen Demand (COD)	Positive	% of removal	61,15	0	79,08	1
Removal efficiency of Biological Oxygen Demand (BOD)	Positive	% of removal	20	0	77,29	1
Removal efficiency of Faecal Coliforms (FC)	Positive	% of removal	90,09	1	79,27	0
Removal efficiency of Total Nitrogen	Positive	% of removal	5,25	1	-	0
Removal efficiency of Phosphorus	Positive	% of removal	-11,6	0	40,97	1
Complexity of initial phase	Negative	[-]; 0 simple - 10 extremly complicated	-	0	1	1
Accessibility provided through infrastructure for O&M	Positive	0 does not apply - 10 applies to full extent	7,7	1	5	0
Time required for the initial phase	Negative	[yr]	9	0	1	1
Complexity of O&M	Negative	0 simpleto - 10 extremly complicated	7	0,5	7	0,5
Requirement of skilled staff	Negative	[-]	0	1	1	0
Requirement of training for staff	Negative	[-]	0	1	1	0
Puffer capacity	Positive	[-]	1373	1	672	0
SUM				**8,5**		7,5

Table 18: Direct comparison within the environmental dimension by assigning points of 0, 0,5 or 1 to the WWTPs for each indicator.



			EP		SPM	
Environmental Indicator	**Impact**	**[Unit]**	**To normalise**	**Nornalised**	**To normalise**	**Normalised**
Nutrients recovery	Positive	[mg P/L]	0	0,5	0	0,5
	Positive	[mg N/L]	0	0,5	0	0,5
Sludge reuse	Positive	[kg sludge/ month]	0	0,5	0	0,5
Methane resue	Positive	[kg CH4/month]	0	0,5	0	0,5
Water reuse	Positive	[m^3 WWreused/m^3 effluent]	-	0,5	-	0,5
Amount of fresh water consumed	Negative	[m^3 fresh water/m^3 WW]	0	0,5	0	0,5
Chemicals consumed	Negative	[kg chemical/m^3 WW]	-	0	0	1
Materials consumed	Negative	[kg material/m^3 WW]	0	0,5	0	0,5
Energy consumed	Negative	[kWh/m^3 WW]	0	0,5	0	0,5
Total Suspended Solids (TSS) in effluent	Negative	[mg/L]	71	1	82	0
Chemical Oxygen Demand (COD) in effluent	Negative	[mg O2/L]	235	0	123	1
Biological Oxygen Demand (BOD) in effluent	Negative	[mg O2/L]	168	0	82	1
Faecal coliforms (FC) in effluent	Negative	[UFC/100 mL]	3,53E+06	1	1,00E+07	0
Total nitrogen (TN) in effluent	Negative	[mg N/L]	155,78	1	-	0
Phosphorus (P) in effluent	Negative	[mg P/L]	17,7	0	11,02	1
Total area required	Negative	[m^2]	2947	0	1493	1
Area of buffer zone	Positive	[m]	50	0	100	1
SUM				**7**		**10**

Table 19: Direct comparison within the social dimension by assigning points of 0, 0,5 or 1 to the WWTPs for each indicator.

			EP		SPM	
Social Indicator	**Impact**	**[Unit]**	**To normalise**	**Normalised**	**To normalise**	**Normalised**
Health impact	Positive	[% of people questioned]	100	0,5	100	0,5
Environmental impact	Positive	[% of people questioned]	85	1	83	0
Satisfaction with sewage system	Positive	[% of people questioned]	42	0	63	1
% of sewage coverage	Positive	[%] = Households connected/Households total	45	0	56	1
Willingness to pay a fair tariff for collection and treatment	Positive	[% of people questioned]	65	0	95	1
Odour	Negative	Yes or no ([% of people questioned])	15	1	45	0
Noise	Negative	Yes or no ([% of people questioned])	0	0,5	0	0,5
Visual impact	Negative	Yes or no ([% of people questioned])	30	0	0	1
SUM				**3**		**5**

Table 20: Direct comparison within the institutional dimension by assigning points of 0, 0,5 or 1 to the WWTPs for each indicator.

			EP		**SPM**	
Institutional Indicator	**Impact**	**[Unit]**	**To normalise**	**Normalised**	**To normalise**	**Normalised**
Available technical human resources	Positive	Yes or no	1	0,5	1	0,5
Available administrative resources	Positive	Yes or no	1	0,5	1	0,5
Available supplies and equipment	Positive	Yes or no	1	0,5	1	0,5
Record of flows	Positive	Yes or no	0	0,5	0	0,5
Record of analysis of the quality of wastewater	Positive	Yes or no	1	0,5	1	0,5
Plans of the infrastructure	Positive	Yes or no	1	0,5	1	0,5
Number of communication events with users	Positive	Yes or no	1	0,5	1	0,5
Number of annual socialized reports with users	Positive	[-]	1	0,5	1	0,5
Level of salary	Positive	[US-$/hour]	2,03	0	3,99	1
Safety conditions	Positive	Yes or no	1	1	0	0
Property of land and fixed activities	Positive	[%] = m^2 property/m^2 total	100	0,5	100	0,5
Auto-sustainable financing (own means)	Positive	[US-$/month]	1	1	-	0
SUM				**6,5**		**5,5**

10.5 Appendix E: Identification of significant indicators

Table 21: The weighting of the dimensions, the ranking result and their normalisation.

		Dimensions		Indicators	
Dimensions	**Indicators**	Sum of points	Normalisation	Tot. Norm.	Dim. Norm.
Economic	Construction cost	24,0	0,50	**0,228**	0,200
	Land cost			**0,067**	0,029
	Cost subsidy from government			**0,201**	0,171
	Operational cost			**0,978**	**1,000**
	Maintenance cost			**0,790**	0,800
	Administration cost			0,388	0,371
	Budget for unexpected repairs			0,308	0,286
	Money available to reinvest (higher purification)			**0,040**	**0,000**
Technical	Amount of wastewater received and treated	23,0	0,43	**0,961**	**1,000**
	Oil and greases			0,398	0,392
	Removal efficiency of TSS in the pre-treatment			**0,234**	0,215
	Removal efficiency of TSS			**0,094**	0,063
	Removal efficiency of COD			0,398	0,392
	Removal efficiency of BOD			0,328	0,316
	Removal efficiency of FC			0,270	0,253
	Removal efficiency of TN			**0,164**	0,139

	Removal efficiency of P			**0,035**	**0,000**
	Complexity of initial phase			0,563	0,570
	Accessibility provided through infrastructure for O&M			0,738	0,759
	Time required for initial phase			0,551	0,557
	Complexity of O&M			**0,832**	0,861
	Requirement of skilled staff			0,703	0,722
	Requirement of training for staff			0,363	0,354
	Buffer capacity			**0,117**	0,089
Environment	Nutrients (N and P) recovery	17,0	**0,00**	0,469	0,556
	Sludge reuse			0,281	0,200
	Methane reuse			**0,176**	**0,000**
	Water reuse			0,633	0,867
	Amount of fresh water consumed			0,422	0,467
	Amount of chemicals consumed			0,457	0,533
	Amount of materials consumed			0,316	0,267
	Energy consumed			0,539	0,689
	TSS in effluent			0,363	0,356
	COD in effluent			0,398	0,422
	BOD in effluent			0,563	0,733
	FC in effluent			0,703	**1,000**
	TN in effluent			0,492	0,600
	P in effluent			0,352	0,333

	Total area required			0,340	0,311
	Area of buffer zone (odour, noise)			**0,246**	0,133
Social	Awareness of the health impact	25,0	**0,57**	0,680	**1,000**
	Awareness of the environmental impact			0,586	0,857
	Level of satisfaction with sewage system			0,445	0,643
	% of sewage coverage			0,375	0,536
	Willingness to pay for collection and treatment of the WW			**0,234**	0,321
	Odour emission			0,609	0,893
	Noise emission			**0,047**	0,036
	Visual impact			**0,023**	**0,000**
Institutional	Availability of technical human resources	31,0	**1,00**	**1,000**	**1,000**
	Availability of administrative human resources			0,547	0,547
	Availability of supplies and equipment			0,672	0,672
	Record of flows			0,531	0,531
	Record of analysis of the quality of wastewater			0,313	0,313
	Plans of the infrastructure			**0,062**	0,062
	Number of communication events with users			**0,125**	0,125
	Number of annual socialized reports with users			**0,031**	0,031
	Level of salary			0,484	0,484
	Safety conditions (clothes, hygiene and health)			0,344	0,344
	Property of land and fixed activities			**0,000**	**0,000**
	Auto-sustainable financing (own means)			0,766	0,766

Ranking results with respect to the entire set of indicators for each dimension

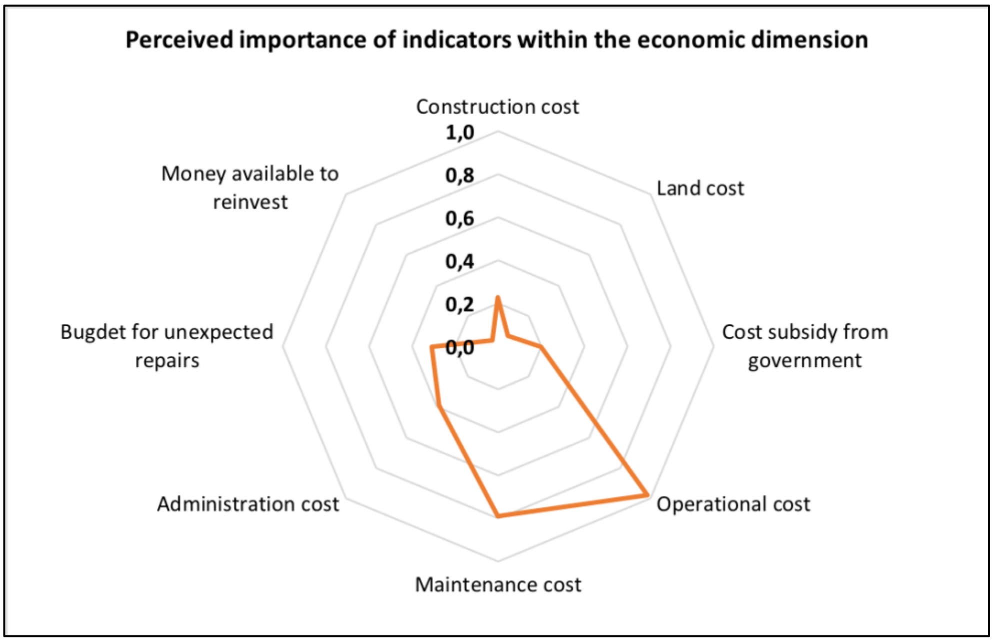


Figure 52a: Achieved total ranking for the economic indicators.

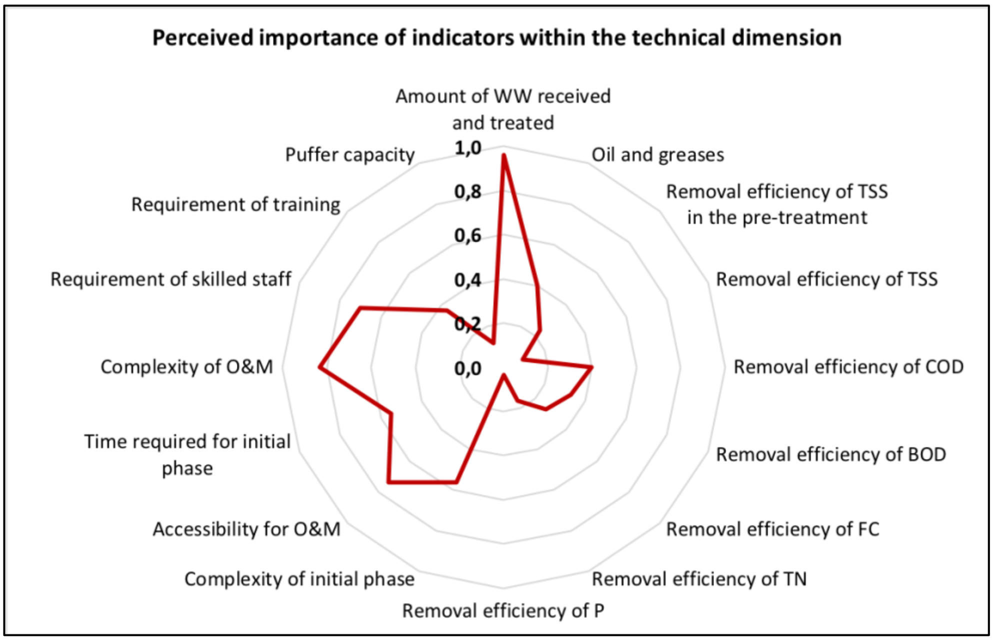


Figure 52b: Achieved total ranking for the technical indicators.

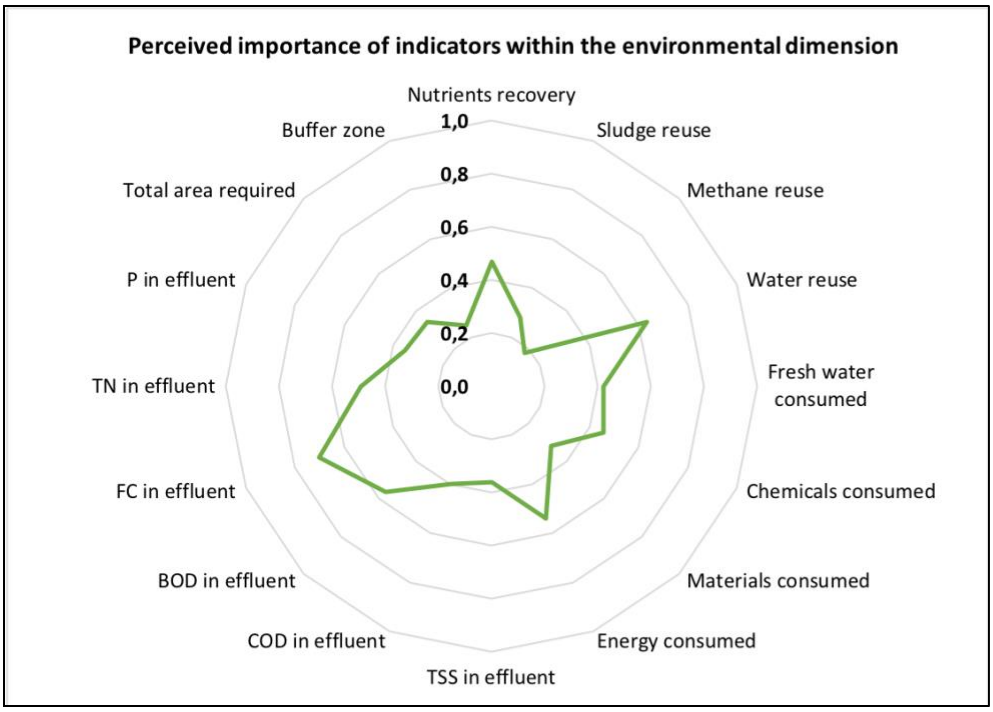


Figure 52c: Achieved total ranking for the environmental indicators.

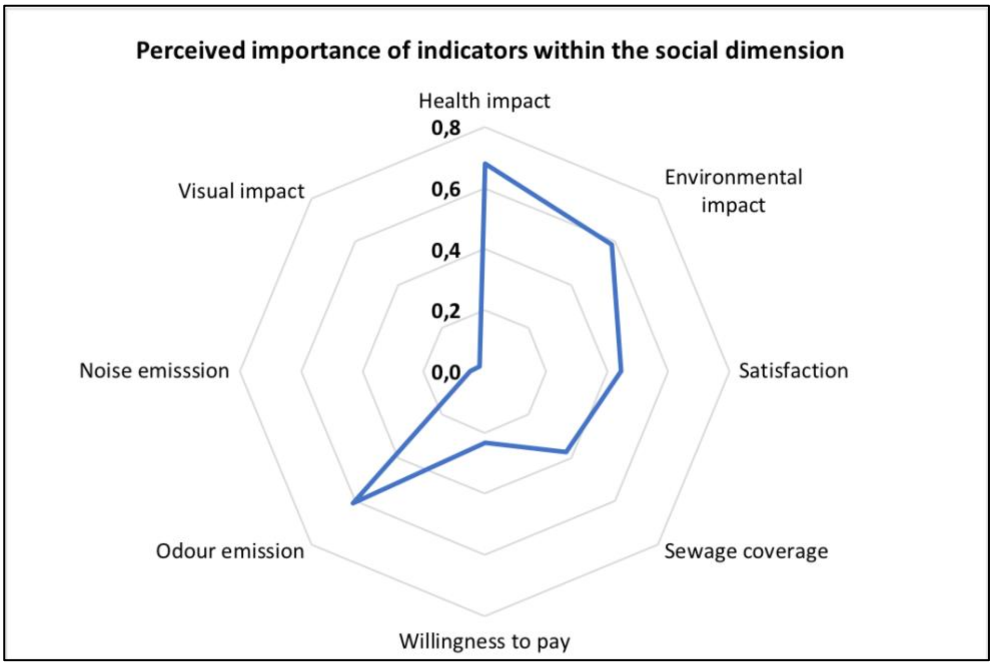


Figure 52d: Achieved total ranking for the social indicators.

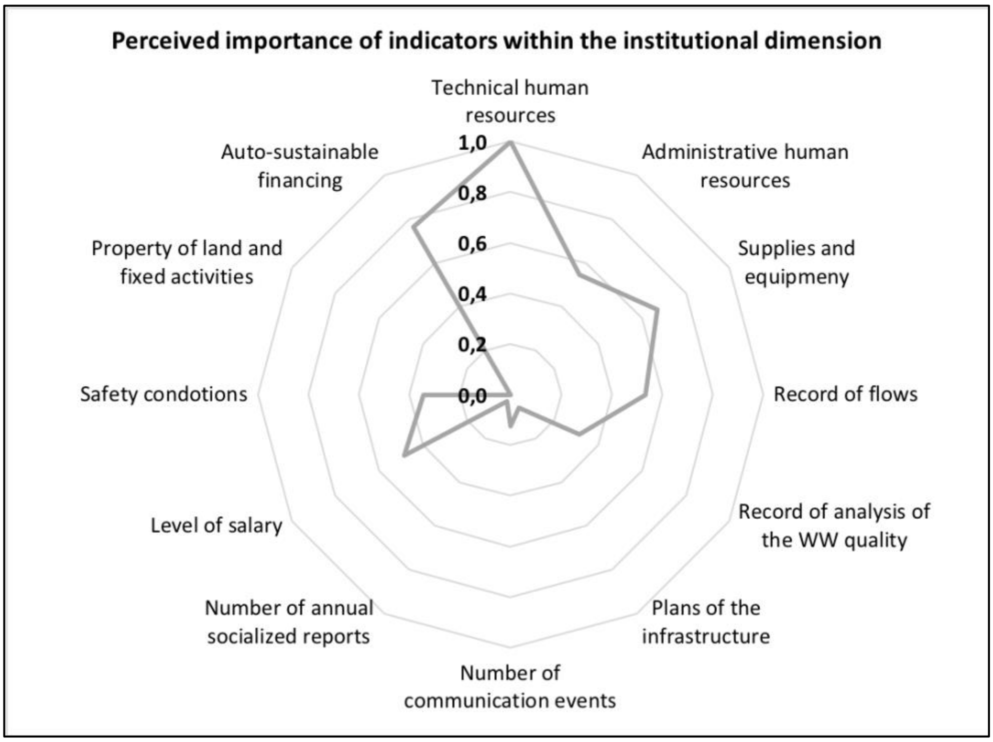


Figure 52e: Achieved total ranking for the institutional indicators.

Ranking results within each dimension

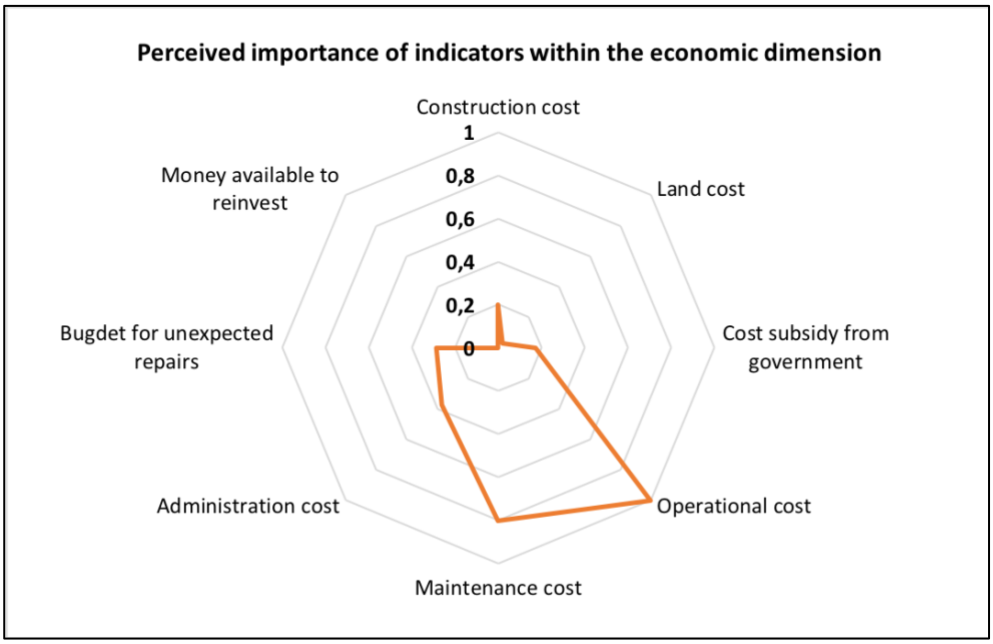


Figure 53a: Achieved ranking within the economic dimension for its indicators.

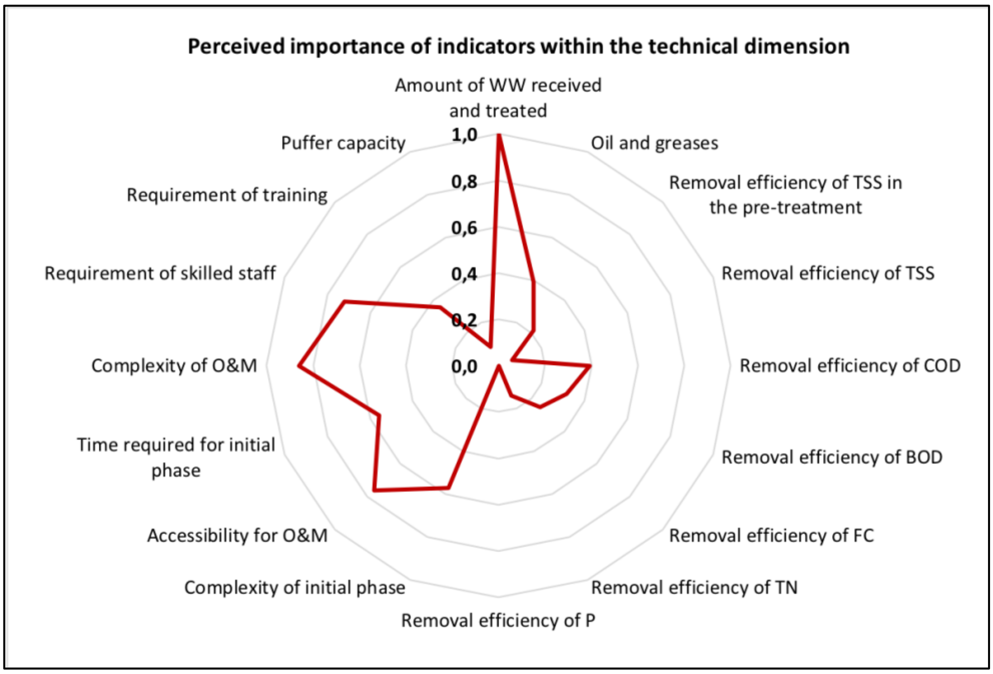


Figure 53b: Achieved ranking within the technical dimension for its indicators.

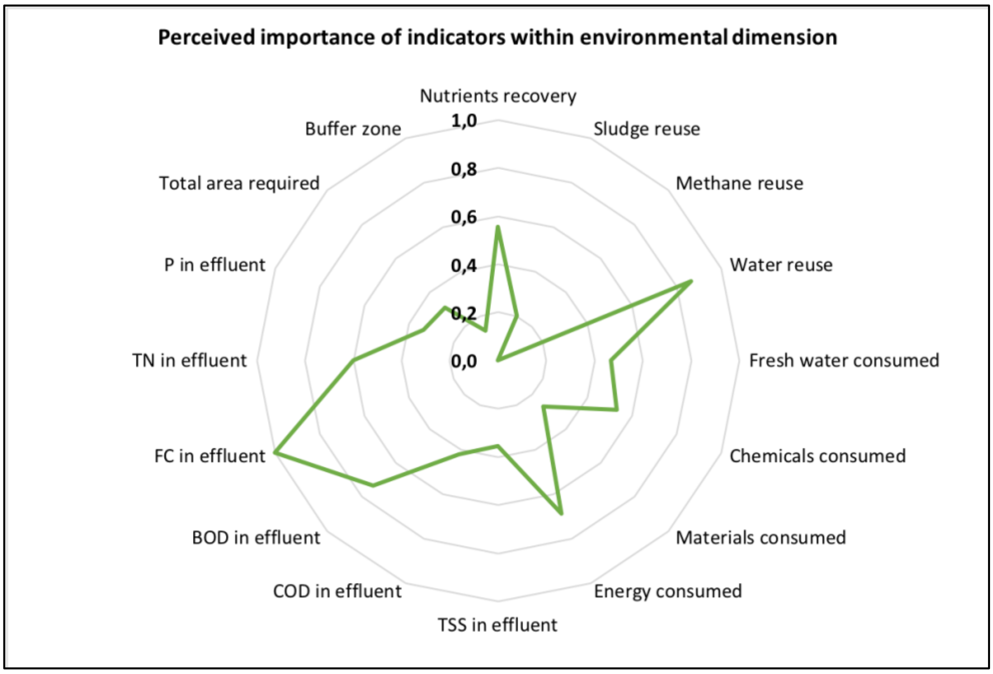


Figure 53c: Achieved ranking within the environmental dimension for its indicators.

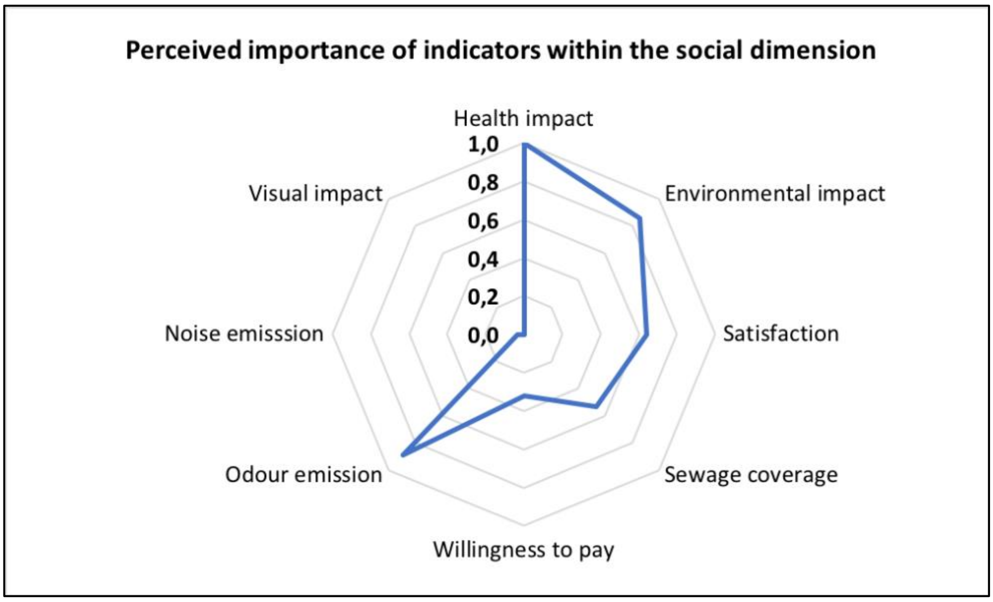


Figure 53d: Achieved ranking within the social dimension for its indicators.

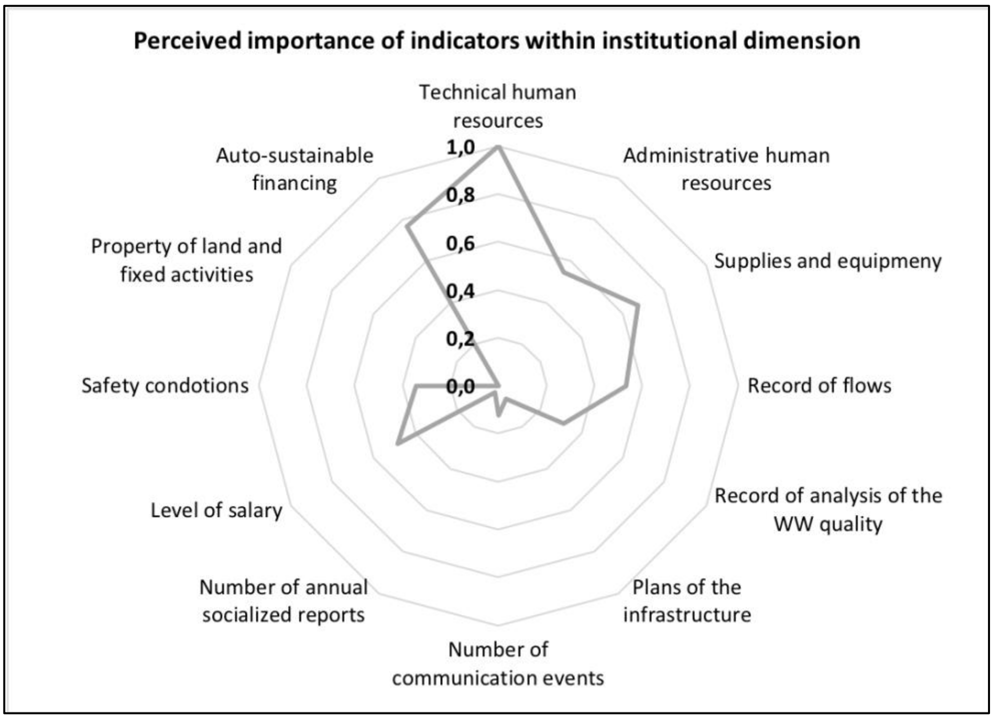


Figure 53e: Achieved ranking within the institutional dimension for its indicators.