WASTEWATER MANAGEMENT IN THE BASIN OF LAKE ATITLAN: A BACKGROUND STUDY

LAURA FERRÁNS, SERENA CAUCCI, JORGE CIFUENTES, TAMARA AVELLÁN, CHRISTINA DORNACK, HIROSHAN HETTIARACHCHI

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Wastewater Management in the Basin of Lake Atitlan: A Background Study

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ABSTRACT

This working paper presents a study on the current wastewater management situation in the basin of Lake Atitlan, Guatemala. The study was performed in 2017, and the results reveal that, in the region, faecal material and urine are disposed of via off-site and on-site sanitation systems. Fifty-five per cent of the community is connected to a sewage system and the remaining 45% use latrines, septic tanks, or soak latrines. In the area of sewage production, 45,500 m^3 of wastewater is generated every day in the basin, and only approximately 20% receives treatment. Moreover, in the existing Wastewater Treatment Plants (WWTPs), one of the most crucial challenges is their poor performance with regard to removal of pathogens and nutrients. WWTPs face, among others, operation and maintenance problems. The most common bottlenecks are the lack of laboratory facilities, constant technical training, handling plan for by-products, personnel and supplies, operation and maintenance manuals, and willingness to pay for users. In the future, sustainable wastewater management strategies should be developed to address the problems of inappropriate wastewater management in the region.

Keywords: wastewater treatment, wastewater treatment plants (WWTPs), faecal waste diagram, operation and maintenance, water quality, Lake Atitlan

1. Introduction

Sanitation is defined by the World Health Organization (WHO) as "the provision of facilities and services for the safe disposal of human urine and faeces" (2018). Due to the high content of pathogens in urine and faecal matter, inadequate sanitation may cause severe impacts to human health; conversely, improved sanitation can bring good health to households and communities (WHO 2018). However, sanitation and wastewater are not well-linked between them. Sanitation processes are not only related to the maintenance of proper hygienic conditions, but also to other services like garbage collection and wastewater disposal (WHO 2018). People around the world generate approximately 2,200 km^3 of wastewater per year, and 80% of it is released into the environment without treatment. The related pollution profoundly affects ecosystems especially water bodies (UNWWAP 2017).

Particularly in Latin America and the Caribbean (LAC), the coverage of improved sanitation varies throughout the region. As shown in Figure 1, in 2015, the rate of access falls between 95–99% for Argentina, Chile, Costa Rica, and Uruguay, and 50–68% for countries such as Guatemala, Bolivia, and Nicaragua. Haiti had the least access represented by 28% (UN-ECLAC 2017a). It clearly appears that despite many countries having reached good sanitation access, Latin America still faces many water and sanitation challenges. One instance is the percentage of treated wastewater falling between 20 and 30% of the wastewater collected in municipal sewerage (UNWWAP 2017).

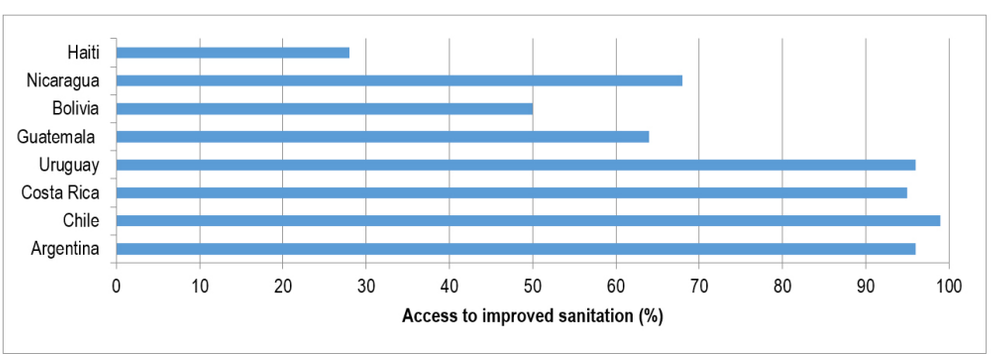

Figure 1: Access to improved sanitation in different countries from LAC in 2015. Adapted from (UN-ECLAC 2017a)

Additionally, the region faces four more main challenges. The first one is with regard to urbanisation. Currently, 80% of the population lives in urban areas and, by 2050, the percentage is expected to rise to 86% (UNWWAP 2017). For cities, sewage is a critical concern. Several towns lack adequate facilities to treat their wastewater, and as a result, areas near water bodies receive untreated effluents. Rivers, lakes, and coastal waters become heavily polluted. Not only is the environment affected, but also human health and economic activities. The second challenge is regarding the operation and maintenance of wastewater

treatment plants (WWTPs). In the region, at a national level, there is a lack of sustainable wastewater management programmes. In many cases, municipalities or small communities create initiatives to build WWTPs. With time, due to the lack of technical and financial capacity, many systems are malfunctioning or abandoned (UNWWAP 2017). Thirdly, often, Latin American municipalities lack technical support for the operation of WWTPs, and therefore, many plants have a poor performance with low removal rates. Finally, another significant challenge is the scarcity of data related to wastewater management. Information about small WWTPs is insufficient, and specifically, information about the amount and quality of produced wastewater is rarely available (Cossio et al. 2017).

Upon identifying the current wastewater management problems present in LAC, evidence points out that a more holistic approach is necessary and that sustainable development must be adopted and implemented. Many articles have defined sustainable development, but the most quoted definition is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCSD 1987). Particularly, United Nations' Sustainable Development Goal (SDG) 6.3 calls for joint efforts to improve water quality, reduce pollution, eliminate dumping, minimise hazardous releases, reduce the amount of untreated wastewater, and substantially increase the safe use of wastewater (UN 2016). The first step to start developing sustainable wastewater management strategies lies in understanding the current situation and determining baseline information (Silva 2013).

In this context, the objective of this working paper is to shed light on the wastewater situation in Guatemala through a case study conducted in a specific area – the Lake Atitlan basin. The water body has high importance due to its water reservoir and because it is the basis of the local economy (DEMUCA 2012). Currently, the lake has started to exhibit eutrophication processes, and one of the leading sources of nutrient inputs is wastewater effluents (Dix and Reyes 2014). Additionally, sewage discharges also contribute to increasing the pathogens contained in the lake, which is a source of drinking water for many communities in the region. It is essential to urgently create sustainable wastewater management strategies that can stop the untreated wastewater effluents from ending up in the lake and improve the environmental and human health conditions (AMSCLAE n.d.).

To contribute to the development of the region of Lake Atitlan (Figure 2) this study specifically intends to investigate the wastewater quantity and quality, availability of WWTPs, and the corresponding removal rates for nutrients, suspended solids, and organic matter in the basin of Lake Atitlan. Additionally, this paper also aims to identify the source of current failures during the operation of existing WWTPs. Ultimately, the study hopes to inform future wastewater management strategies in the region, and especially in small and medium-sized cities.

Figure 2: Lake Atitlan, Guatemala in June 2017 (Image credit: Laura Ferrans)

2. Regional Settings of the Study Area

2.1 General Aspects of Guatemala

According to the United Nations Economic Commission for Latin America and the Caribbean (UN-ECLAC), in 2017, the estimated population in Guatemala was 16.5 million inhabitants. In 2014, 58% of the urban population lived in poverty and 33.7% in absolute poverty. In the rural areas, 77% of the population lived in poverty and 58.2% in total poverty (UN-ECLAC 2017c) (see Figure 3). UN-ECLAC also established that in 2016, the Gross Domestic Product (GDP) of Guatemala was USD 4.147 per person (UN-ECLAC 2017b), in contrast to the average GDP of Latin America at USD 8.820 per person (UN-ECLAC 2017d). In brief, Guatemala is the largest country in Central America; its economy is weaker than the average in Latin America and poverty is one the country's central issues. Regarding environmental aspects, according to Guzman and Quiñonez (2014), wastewater management can be classified as a large-scale challenge due to the influence of several variable factors such as lack of territorial planning, high population growth concentrated in urban areas, and little demand for environmental legal compliance, among others. As a result, in 1995, the coverage of WWTP was only 8% (Guzman and Quiñonez 2014).

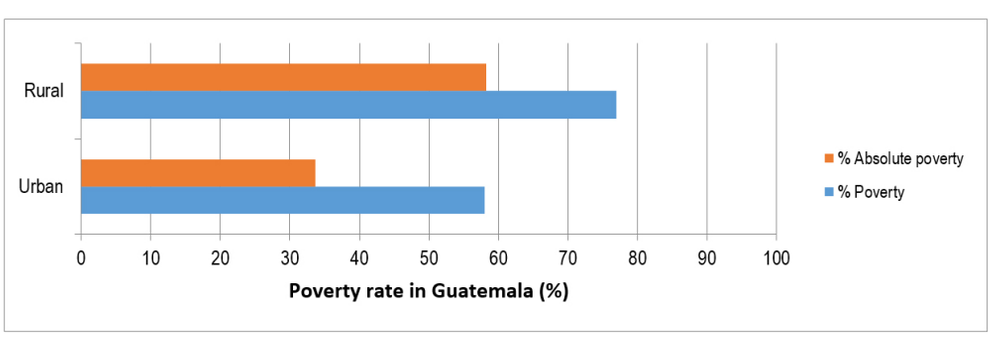

Figure 3: Poverty level in rural and urban areas from Guatemala in 2014. Adapted from (UN-ECLAC 2017c)

2.2 Location and Population of the Lake Atitlan Basin

Lake Atitlan is located in the south-western part of Guatemala in a crater of an old volcano situated in the municipality of Sololá (Figure 4). The elevation ranges from 1,562 to 3,587 metres above sea level (USAC 2015). More than 50% of the watershed consists of steep slopes (Komarek et al. 2013), and three volcanoes (Tolimán, Atitlán, and San Pedro) surround the water body.

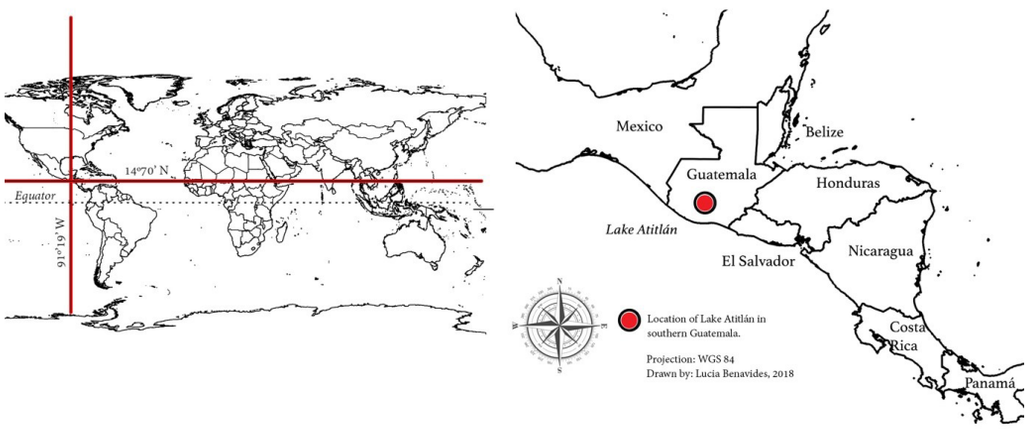

Figure 4: Location of Lake Atitlan (Image credit: Lucia Benavides)

According to AMSCLAE (2013), the basin comprises of 15 municipalities. Table 1 lists all towns belonging to the catchment (AMSCLAE 2013) and Figure 10 shows their locations on a map. The population in the basin area is projected by the National Statistics Institution (INE) to be approximately 380,400 inhabitants for the year of 2017 (INE n.d.). Table 1 also shows the size of the population for each municipality. Furthermore, 95% of the population is indigenous, and the present ethnicities are Tz'utujil, Kiche, and Kaqchikel (AMSCLAE 2013). Finally, 70% of the population live in poverty and 32% in absolute poverty (Dix and Reyes 2014).

Table 1: Population in municipalities in Lake Atitlan basin

Map Icon (Figure 10)	**Municipality**	**Population projection for 2017 (INE)**
1	Sololá	149,951
2	Santiago Atitlan	52,046
3	San Lucas Tolimán	33,986
4	Santa Lucia Utatlán	26,944
5	Panajachel	20,387
6	San Antonio Palopó	14,289
7	San Andrés Semetabaj	14,649
8	San Pedro la Laguna	12,210
9	San Juan la Laguna	12,247

Map Icon (Figure 10)	Municipality	Population projection for 2017 (INE)
10	Santa Cruz la Laguna	9,027
11	San Pablo la Laguna	8,174
12	Concepción	7,809
13	Santa Catarina Palopó	7,363
14	San José Chacayá	5,871
15	San Marcos la Laguna	5,546
	Total	**380,499**

Source: INE n.d.

2.3 Economy of the Region

Tourism is the primary driver of the economy in the region since Lake Atitlan is one of the most beautiful lakes in the world. The services sector also has a significant contribution. In the area, there are several restaurants, hotels, grocery stores, handicraft stores, and transportation (bus and boat) companies. For municipalities where tourism is not essential, agriculture and livestock are the most important economic drivers. Typical crops are coffee, corn, beans, wheat, potatoes, sugar cane, and vegetables (Sánchez 2001). Finally, in the basin, 22% of the population work in agriculture, 20% are merchants, 14% self-employed, 10% wage labourers, 9% housewives, 6% artisans, and 16% are dedicated to other labour (Rivera 2011).

2.4 Hydraulic Characteristics of Lake Atitlan

The basin has an area of 541 km^2 where 127 km^2 represent the lake surface, and 414 km^2 are part of the drainage area. The maximum lake's depth is 330 m and the average 220 m. Its total volume is 24.4 m^3 and its hydraulic retention time is approximately 80 years (USAC 2015). Also, the water body is of the endorheic type. The hydrological system is thus closed and only has underground outputs. Its primary water inputs are precipitation, runoff, and river discharges (CONAP 2006). The most common aquatic plants are tulle, hydrilla, and nymph (Sánchez 2001). Tulle is a native species of high importance since it provides habitat for molluscs, crustaceans, fish, insects, and waterfowls (CONAP 2006). Additionally, the plant is essential for some artisans who use its leaves to make handicrafts (Rejmánková n.d.).

2.5 Water Quality of Lake Atitlan

The problem of water quality in Lake Atitlan is a complicated one where many factors are involved. As stated by Romero (2009), nowadays, the lake is threatened by wastewater disposal, deforestation, erosion, demographic pressure, and lack of environmental awareness, policies, strategies, and actions. The two main contaminant concerns are nutrients and pathogens and heavy metals are of little interest. Figure 5 illustrates the primary pollutants at the lake and their related sources.

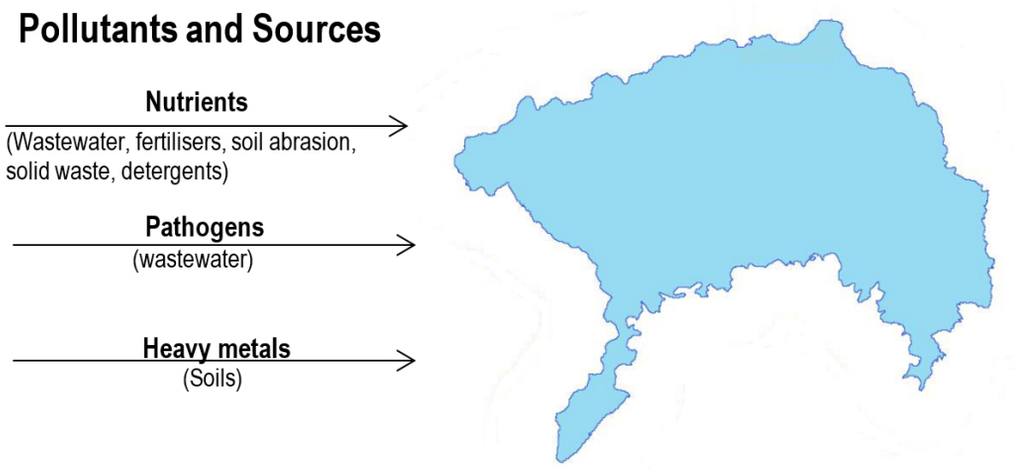

Figure 5: Main pollutants present in Lake Atitlan and their respective input sources

2.5.1 Pollution by Organic and Inorganic Substances

2.5.1.1 Nutrients

Currently, water quality in the lake is affected by elevated nutrient inputs. The phosphate concentration in 2013 was five times higher than in 1983 and, similarly, nitrate content is ten times higher in 2013 than in 1968 (AMSCLAE 2013). Due to the high input of nutrients, since 2008, periodic bacteria blooms have affected the water body (see Figure 6) (Komarek et al. 2013). Aesthetic and ecological aspects of the lake have been modified (Komarek et al. 2013). Additionally, some cyanobacteria species produce harmful toxins. Therefore, wildlife and human health can also be affected (Romero 2013). Moreover, currently the state of the lake is changing from oligotrophic to mesotrophic; hence, actions must be taken in the near future to stop this deterioration process (Dix and Reyes 2014).

Sources of phosphorous and nitrogen include untreated and partially treated wastewater effluents, fertiliser input from runoff of agricultural fields, abrasion of soils, solid waste, and detergents directly used in the lake (Romero 2013, Dix and Reyes 2014). Wastewater effluents, fertiliser inputs, and organic waste are rich in nutrients due to their specific nature. As for erosion, soils from the region have high levels of phosphorus. Additionally, detergents are also considered as a source of phosphorus since they contain inorganic phosphate (Romero 2013).

Figure 6: Cyanobacteria bloom in 2009 at Lake Atitlan (Image credit: Eliska Rejmankova)

2.5.1.2 Heavy Metals

In the region, there is no presence of industry (except for small textile industries (Genaro Umul, personal interview, May 29, 2017), and therefore heavy metals have low concentrations in the lake. However, arsenic levels do not meet the standards of the Guatemalan drinking water regulation. The soils of volcanic origin, characteristic of the area, are the source of arsenic in the region. Since the lake is a source of drinking water and the metal has toxic effects on human health, efforts are urgently needed to develop projects for finding economic and eco-friendly technologies to remove the arsenic (Pérez-Sabino et al. 2015).

2.5.2 Pollution by Pathogens

Non-disinfected wastewater effluents introduce pathogens to the lake. Discharges commonly include microorganisms such as coliforms, *E. coli*, and parasites. The concentration of the species varies around the lake. The primary concern is within close proximity to the municipalities. In front of Panajachel, in 2013, the levels of faecal coliforms and *E. coli* were 5,600 and 1,100 MPN/100 ml. In the centre of the lake, the microorganisms reduced to 70 and 1 MPN/100 ml (Romero 2013).

2.6 Impacts on the Region due to Inappropriate Wastewater Management

Due to raw and partially treated wastewater discharges into the lake, it is possible to identify several impacts on the region. In detail, effects can be classified into health, lake ecosystem, and economy. Figure 7 illustrates all identified impacts.

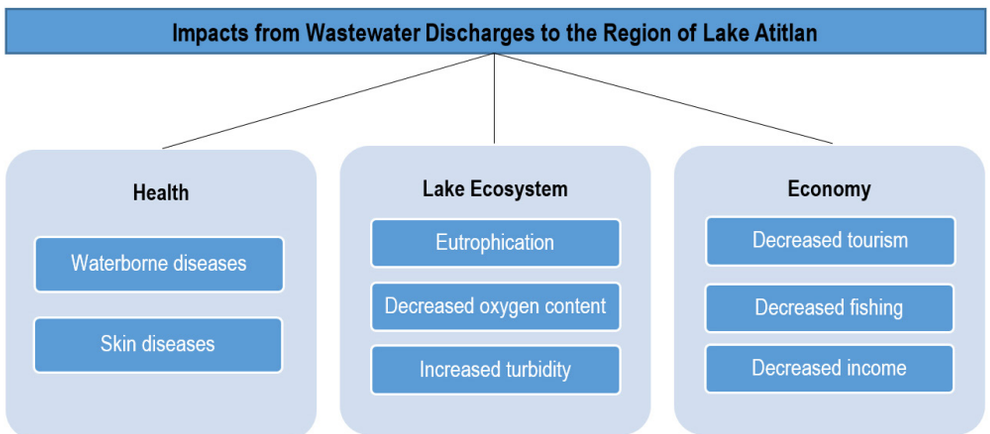

Figure 7: Human health, lake ecosystem, and economic impacts caused by wastewater discharges

2.6.1 Impacts on Human Health

Lake Atitlan serves as the primary source of drinking water for more than 70,000 inhabitants from at least five municipalities (Orozco 2017). Between 90–100% of the population from San Lucas Atitlan, Santiago Atitlan, and San Pedro consume water from the lake (AMSCLAE 2013). In several cases, WWTPs have a low level of disinfection, and therefore human health can be severely affected (Monica Orozco, personal interview, June 8, 2017). Wastewater effluents transmit several waterborne diseases (Romero 2013). Figure 8 illustrates percentages of the population who have suffered illnesses related to wastewater in the region of Lake Atitlan.

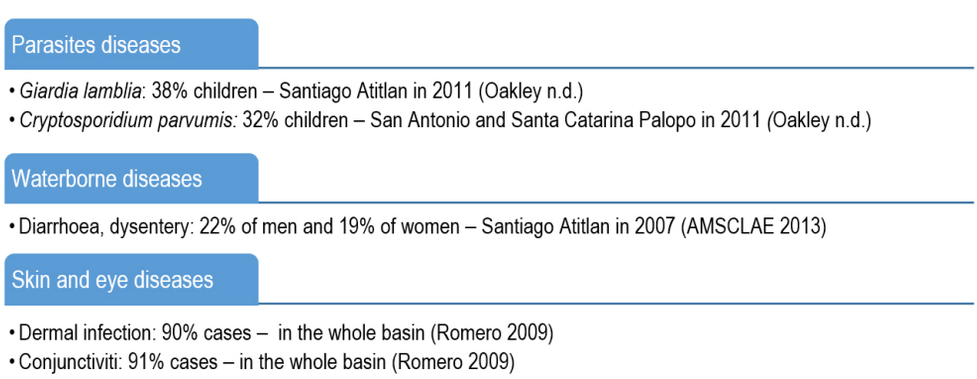

Figure 8: Diseases caused by wastewater discharges in the region of Lake Atitlan
Modified from: Oakley (n.d.), AMSCLAE (2013), and Romero (2009)

2.6.2 Environmental Impacts on the Lake

Wastewater discharges are also responsible for several ecological effects in Lake Atitlan. As described before, nutrient inputs change the lake's dynamics and promote eutrophication processes which affect the ecology of the lake (Chandra et al. 2014). However, nutrients are not the only parameters of concern. Organic and chemical materials increase the oxygen demand from wastewater. Sewage without treatment has a high biological oxygen demand (BOD) and chemical oxygen demand (COD). When raw wastewater is discharged into the lake, it consumes available oxygen and therefore lowers the concentration of this element. Less oxygen is available to the plants and organisms of the ecosystem, and this affects their essential functions (Romero 2013). Finally, the solids in wastewater increase turbidity of the lake; less light can penetrate the water body's layers. With this phenomenon, energy budget and temperature profoundly change and affect the dynamics of the ecosystem (Chandra et al. 2014).

2.6.3 Economic Impacts

Wastewater discharges have several implications to human health and the environment of the lake; in addition, the economy of the region can also be affected. Specifically, three consequences are recognised. Firstly, with the deterioration of the water quality of the lake, aesthetical conditions are disturbed. If the lake is polluted, it loses its touristic attraction, and fewer visitors travel to the area. Consequently, one of the leading drivers of the regional economy becomes crippled (Chandra et al. 2014). Secondly, pollution of the lake causes its animal species to diminish, and therefore fishing is reduced. Finally, due to diseases related to wastewater, over the year, people are less productive, and losses of income can be perceived (Dix and Reyes 2014).

3. Wastewater Management in Lake Atitlan

Previously, the impacts related to the mishandling of wastewater have been identified. To contribute to identifying bottlenecks in wastewater management of the region, the upcoming sections intend to shed light on the current wastewater situation in Lake Atitlan. Particularly, the study uses a multi-source approach consulting local reports and available literature to collect data about available sanitation services, amount of wastewater produced, and level of performance and current operational failures of available WWTPs. The reports and dissertations used by this study are entitled: (1) "Caracterización de las aguas residuales generadas en la cuenca del Lago de Atitlán y su impacto" (Romero 2013); (2) "Calidad de las aguas subterráneas en el municipio de San Pedro La Laguna y sus efectos sobre el cuerpo de Agua del Lago de Atitlán" (Escobar and Rodriguez 2017); (3) "Fichas informativas PTAR Cuenca Atitlan" (AMSCLAE, n.d.), and (4) "Informe muestreo de las plantas de tratamiento de aguas residuales de la Cuenca del Lago Atitlan" (AMSCLAE 2015). It is expected that in the future, new projects can make use of the information collected in this study to develop sustainable wastewater management strategies for the Lake Atitlan region.

3.1 Status of Sanitation Services in the Lake Atitlan Basin

Regarding the assessment of sanitation services, several routes for disposing faecal material can be identified in a municipality. On-site systems represent schemes where the excrement treatment is handled at the household level. Conversely, off-site sanitation involves infrastructure such as sewage systems and central WWTPs which are beyond the household level. Specifically at Lake Atitlan, off-site and on-site sanitation systems are present. For off-site systems, no accurate data is available on the amount of water transported through a sewerage system. This study approximates that around 55% of the population of the basin discharge their produced wastewater to sewage systems. According to the estimation of this working paper (calculations are available in section 3.3), WWTPs treat the water generated for 20% of the basin population. The remaining 35% is lost through leakage or directly discharged into the lake or its tributary rivers.

In the area, there are three different routes for the disposal of faecal material using on-site sanitation systems. Based on personal communication with Dr Felix Aguilar, a professor at San Carlos University, in total, 44% of the basin population uses this type of systems. The available routes to dispose of urine and excreta are through septic tanks, soak pits, and dry latrines. There is no data about maintenance of septic tanks and latrines, and therefore it is not possible to state if their discharges are safely handled. As for soak pits, raw wastewater is directly infiltrated in soils. Treatment is not present; hence, fluxes from this system are also classified as unsafely managed. Finally, in the municipality of San Pedro, 1% of the population still practises open defecation (Escobar and Rodriguez 2017). No data for this is available for the entire region of Lake Atitlan; hence, this study adopts the same figure for the practice of open defecation in the basin. Figure 9 visualises all sanitation services for the disposal of faecal matter present in the Lake Atitlan basin.

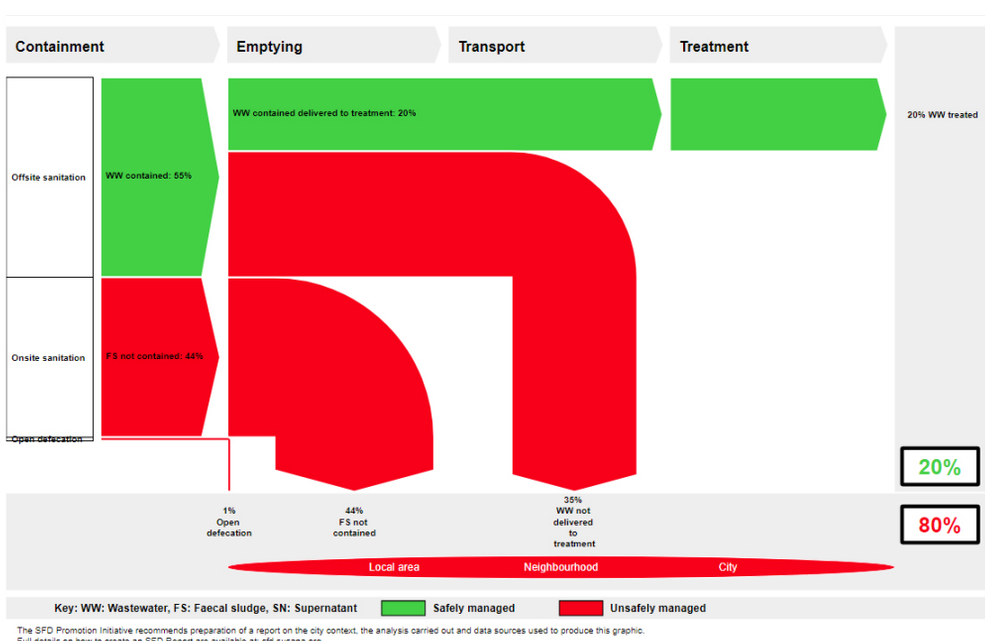

Figure 9: Preliminary faecal diagram for basin of Lake Atitlan
Developed with free software by Sustainable Sanitation Alliance (SuSanA) (http://sfd.susana.org/)

3.2 Amount of Wastewater Produced in the Lake Atitlan Basin

In the municipalities located inside the Lake Atitlan basin, no water consumption data is available. No water flow meters and thus estimation of the wastewater produced exists in the area (Allan Perez, personal interview, May 30, 2017). To approximate the amount of sewage generated in the Lake Atitlan basin, Romero (2013) calculated the water consumption rates related to each municipality surrounding the lake. The study revealed that, in rural areas, the water consumption rate is 100 l/d-inhabitant. The consumption rises to 180 l/d-inhabitant in the urban areas. As an exception, in the municipalities of Panajachel and Sololá, the consumption in urban areas is 250 and 200 l/d-inhabitant respectively. For all cases, the return coefficient is 80%.

Using the water consumption rates and return coefficient provided by Romero (2013), this study calculated the amount of wastewater produced in the Lake Atitlan basin. The community around Lake Atitlan produces approximately 530 litters of wastewater per second (45,500 m^3/day). Table 2 provides the specific amount of sewage generated in each town.

Table 2: Estimation of wastewater production in municipalities in the basin of Lake Atitlan

Municipality	Urban waste-water (l/s)	Rural waste-water (l/s)	Total waste-water (l/s)
Sololá	110	84	194
Santiago Atitlan	81	3	84
San Lucas Tolimán	36	12	47
Santa Lucia Utatlán	3	23	26
Panajachel	42	2	44
San Antonio Palopó	9	8	17
San Andrés Semetabaj	7	10	17
San Pedro la Laguna	20	0	20
San Juan la Laguna	11	5	16
Santa Cruz la Laguna	4	6	10
San Pablo la Laguna	14	0	14
Concepción	8	3	11
Santa Catarina Palopó	8	2	11
San José Chacayá	2	4	6
San Marcos la Laguna	8	1	9
Total	**364**	**163**	**527**

3.3 Available WWTPs at the Lake Atitlan Basin

In the basin of Lake Atitlan, there are 12 WWTPs. Figure 10 shows the location of each facility. Four plants use activated sludge technology, one employs facultative lagoons and septic tanks, and the other eight facilities use anaerobic reactors and biological percolating filters (AMSCLAE n.d., 2015). Table 3 lists all WWTPs along with their capacities, technologies, discharges, and sludge treatment units. According to the calculations of this study, people from the basin produce approximately 530 litres of wastewater per second. The total capacity of all WWTPs is approximately 120 l/s. Hence, only around 20% of sewage can receive treatment. Table 3 also illustrates the discharge routes of treated wastewater. In total, 33% of the treated water is used for crop irrigation, 4% goes directly into the lake, 47% is discharged into the lake's tributary rivers, and 16% is infiltrated in soils. The untreated wastewater is discharged into rivers, directly into the lake, or onto open grounds (Romero 2013).

Table 3: WWTPs available in the basin of Lake Atitlan

WWTP	Municipality	Q_{design} (lps)	Technology	Discharge	Sludge treatment
Cebollales	Panajachel	37	Activated sludge + Chemical flocculation	River – Lake Atitlan	Anaerobic digestion + Drying beds
Chuk Muk	Santiago Atitlan	19	Inhoff + Biological filtration + Facultative pond	Infiltration in the ground	Drying beds
Maria Tecun	Sololá	5	UASB + Biological filtration	River – Lake Atitlan	Drying beds
San Antonio	Sololá	10.5	UASB + Biological filtration	Crop irrigation	Drying beds
San Bartolo	Sololá	24	UASB + Biological filtration + Sand filtration	Crop irrigation	Drying beds
San Jorge la Laguna	San Jorge la Laguna	3.9	UASB + Biological filtration	River – Lake Atitlan	Drying beds
El Novillero	Santa Lucia Utatlán	1.9	Septic tank + Facultative lagoon	River – Lake Atitlan**	Drying beds
San Andres Sametabaj	San Andres Sametabaj	7.5	Inhoff + Biological filtration	River – Lake Atitlan	Drying beds
Santa Catarina Palopo	Santa Catarina Palopo	3	Activated sludge + Aquatic plants for nutrient removal	Lake Atitlan	Aerobic digestion + Drying beds
Santa Cruz la Laguna	Santa Cruz la Laguna	6	Inhoff + Biological filtration	River – Lake Atitlan	Drying beds
San Lucas Toliman	San Lucas Toliman	1	Activated sludge	Lake Atitlan	N.A.
San Marcos	San Marcos	N.A.	SBR + Chlorine dis-infection	Irrigation plant nurseries	Aerobic digestion + Gravitational thickening

Source: (AMSCLAE, n.d.)
UASB: Upflow Anaerobic Sludge Blanket, N.A.: Data not available

In each municipality, the percentage of treated wastewater varies according to the availability and capacity of existing WWTPs. Figure 11 illustrates the portion of treated wastewater for each town located in the basin of Lake Atitlan.

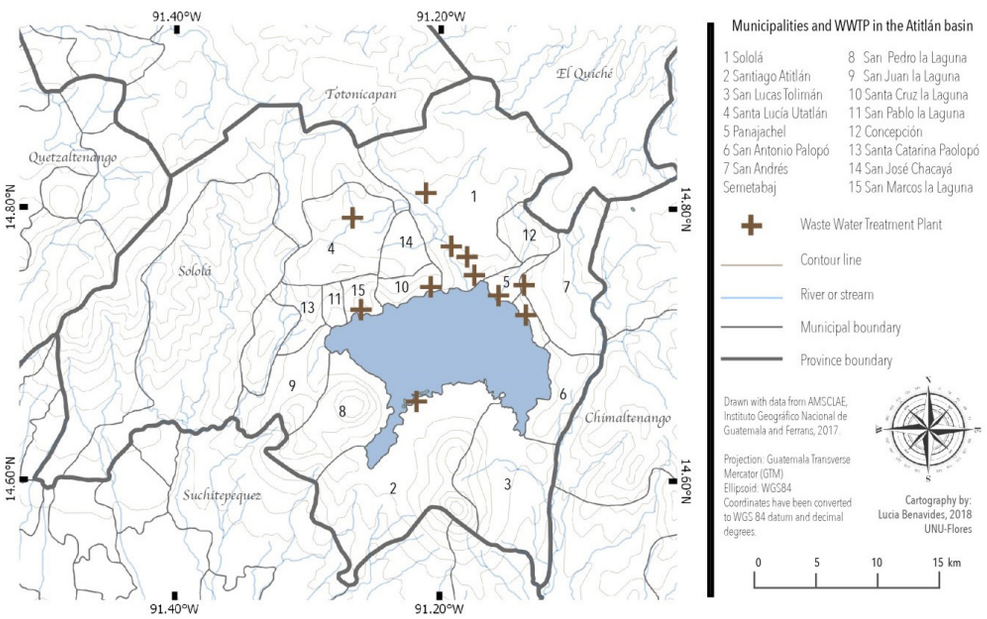

Figure 10: Municipalities in basin of the Lake Atitlan along with available WWTPs (Image credit: Lucia Benavides)

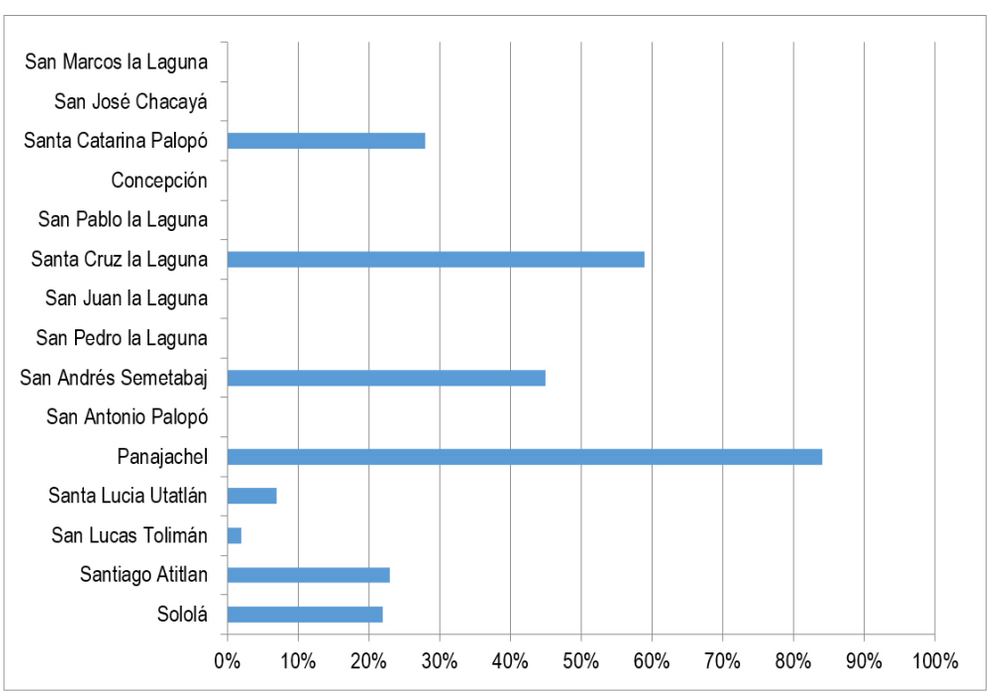

Figure 11: Percentage of treated wastewater at each municipality around Lake Atitlan

3.4 Performance of WWTPs Located in the Lake Atitlan Basin

Regarding the performance of the WWTPs at Lake Atitlan, this study uses the most recent data available from the Authority for the Sustainable Management of Lake Atitlan basin (AMSCLAE) from the year 2015. Available measurements include chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and total coliforms to calculate the level of performance of the different WWTPs (AMSCLAE 2015). Table 4 and Table 5 illustrate the characterisations of the WWTPs' outflows along with the corresponding national thresholds. Regarding the compliance with the local regulation (Acuerdo Guvernativo #12-2011), the only parameter within the range of the local limits was the pH. Other parameters rarely met the regional levels established by local regulation.

Concerning removal rates, in 2015, the WWTPs in Santa Cruz la Laguna and San Lucas Tolimán were malfunctioning, and there was no significant removal of any contaminant. Additionally, the WWTP from San Marcos had not been constructed. From the remaining seven WWTPs, COD, BOD, and TSS achieved average removal rates of 68%, 78%, and 83% respectively. Nutrients were poorly removed (average removal of approx. 30%), and coliform removal was negligible (all values at the exit of all WWTPs were higher than $5x10^3$ MPN/100 ml). Removal rates were calculated using the characterizations of wastewater influents and effluents at different WWTPs presented by AMSCLAE (2015). Figure 12 presents the average removal rates achieved from WWTPs in 2015.

Table 4: Characterisation of wastewater effluents from WWTP discharge into Lake Atitlan and infiltration

Parameter	Local Threshold*	Santa Catarina	San Lucas	Local Threshold**	Chuk Muk
Discharge	-	Lake	Lake	-	Infiltration
pH (-)	6 to 9	7.69	7.34	6 to 9	9.30
BOD (mg/L)	30	4.5	297	50	35
COD (mg/L)	60	46	543	100	172
PT (mg/L)	3	1.29	3.32	5	6.7
NT (mg/L)	5	1.29	2.3	10	19
TSS (mg/L)	40	5.3	167.4	60	59
Faecal coliforms (MPN/100 ml)	500	86×10^3	$2{,}200 \times 10^3$	1×10^4	86×10^3

* Threshold for direct discharges into the lake from Acuerdo Gubernativo #12-2011,
** Threshold for infiltration discharges from Acuerdo Gubernativo #12-2011.
Red: threshold is not met, Green: threshold is met. Source: AMSCLAE 2015

Table 5: Characterisation of wastewater effluents from WWTP discharge into rivers

Parameter	Local Threshold*	Novillero	Maria Tecun	San Bartolo	San Antonio	San Jorge	Cebollales	Santa Cruz	San Andres
Discharge	-	River	River	River	River	River	River	River	River
pH (-)	6 to 9	9.09	7.31	7.84	7.35	7.43	7.49	7.56	7.63
BOD (mg/L)	50	76	80	40.4	124	175	90	180	107
COD (mg/L)	100	300.3	141.3	233	157.67	405.6	276.6	367.33	207.3
PT (mg/L)	5	8.26	5.12	5.02	5.3	10.5	5.93	4.9	3.8
NT (mg/L)	10	27.8	34	39.6	38.3	>15	25	19.23	19.5
TSS (mg/L)	60	118	26.5	20.2	12.55	83.75	-	109.71	55.3
Faecal coliforms (MPN/ 100ml)	1×10^4	186×10^3	920×10^3	480×10^3	$2{,}200 \times 10^3$	$2{,}200 \times 10^3$	920×10^3	> 4,800	920×10^3

*Threshold for river discharges from Acuerdo Gubernativo #12-2011.
Red: threshold is not met, Green: threshold is met. Source: AMSCLAE 2015

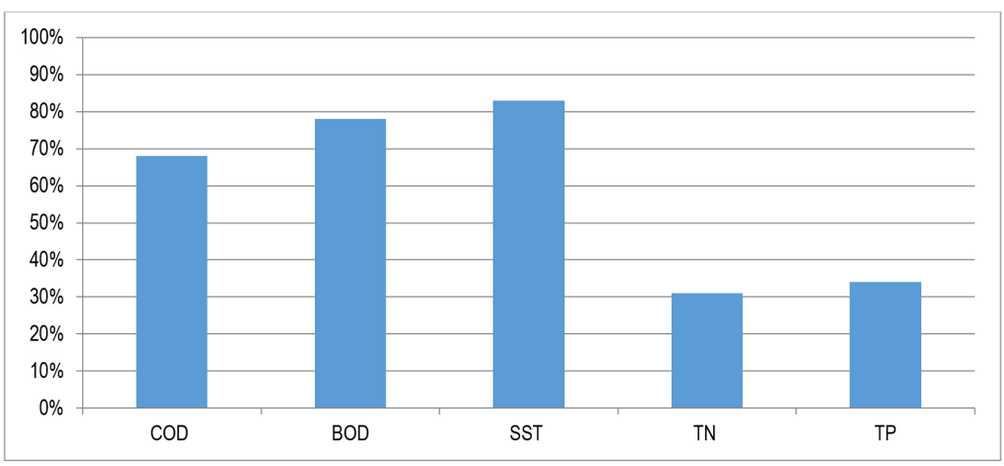

Figure 12: Average removal rates of COD, BOD, SST, TN, and TP from WWTPs located in the Lake Atitlan basin (2015). Adapted from: (AMSCLAE 2015)

3.5 Operation and Maintenance of WWTPs Located in the Lake Atitlan Basin

3.5.1 Bottlenecks

This study identifies operation and maintenance (O&M) bottlenecks through inspection visits and interviews with main stakeholders. The presented problems commonly exist in all WWTPs. The following section lists the identified aspects. Figure 13 represents all identified bottlenecks along with suggestions for potential solutions.

(1) Laboratory facilities: According to the inspections made in this study, the majority of WWTPs lack on-site laboratory facilities (only the newest plant from San Marcos has this type of facility). As a consequence, the plants lack quality monitoring projects, and the functionality of treatment units can only be calculated by using yearly characterisations.

(2) Personnel and supplies: Frequently, WWTPs face several problems related to personnel, supplies, and reagents. For all activated-sludge WWTPs (four in the basin), the operation and maintenance costs are excessively high, and municipalities can barely cover them. This type of plants requires permanent supervision which results in high demand of operators. Costs also rise due to the consumption of electricity related to the air supply and pumping. Additionally, spare parts (such as diffusers and parts for the aeration system) are constantly required.

(3) Discontinuous management: One of the biggest problems related to WWTPs and recognised by several stakeholders is the lack of continuous management (Susana Heisse, personal interview, June 5, 2017; Monica Orozco, personal interview, June 8, 2017; Patricia Mort and José Ramos, personal interview, June 7, 2017). In Guatemala, local governments change every three years. When a new government is established, frequently, the new administration neglects the previous management programmes. The same situation occurs for WWTPs, where the monetary resources and personnel change at the beginning of each new local government term. As a consequence, the management of WWTPs is discontinuous and good results are difficult to achieve.

(4) Quality compliance: WWTPs located at the Lake Atitlan basin are not designed to remove nutrients and pathogens (Allan Perez, personal interview, May 30, 2017; Monica Orozco, personal interview, June 8, 2017). Treated wastewater generally is without organic material and suspended solids; however, nitrogen, phosphorous, and microorganisms were found to be still present. Nutrient contributions should be eradicated to avoid the eutrophication of the lake. In the same way, pathogen inputs must be eliminated to improve the health of people who consume water from the lake.

(5) Capacity: There are two problems related to the amount of wastewater treated in the basin. First, WWTPs cannot treat all wastewater generated in the region. The coverage is designed for around 20% of the produced wastewater, and the remaining 80% is discharged without treatment (Felix Aguilar, personal interview, May 25, 2017). Second, few households are connected to the sewage system, and therefore, even if WWTPs would have higher capacities, wastewater could not be transported to the treatment plants. Additionally, the topography of the area is very steep. Hence, the expansion of the sewer systems can be costly and complicated to perform (Ernesto Celada and Zindy Garcia, personal interview, June 7, 2017).

(6) Training: Another important problem identified during the inspection visits of this study and by several stakeholders is the lack of training and technical support. Frequently, managers and operators lack the skills and know-how to operate the plants. As a result, WWTPs are malfunctioning systems where basic processes are not well performed (Allan Perez, personal interview, May 30, 2017). Technical support from authorities or scientific experts is missing at municipal and private WWTPs (Patricia Mort and José Ramos, personal interview, June 7, 2017).

(7) Solid waste: Based on the inspection visits, in all WWTPs, the solid waste removed during pre-treatment is buried on grounds belonging to the plants. In some cases, the waste is treated with lime, but most of the time the waste is dumped without any treatment. Dumping of this waste can result in environmental pollution related to soil and aquifer contamination.

(8) User payment: As stated by some stakeholders (Allan Perez, personal interview, May 30, 2017; Monica Orozco, personal interview, June 8, 2017), currently communities are not willing to pay for wastewater management services. In the area, users only pay an insignificant tariff (around EUR 1 per month) for water supply (Allan Perez, personal interview, May 30, 2017). As a result, local authorities must provide subsidies for wastewater systems. In many cases, the available budget is not enough to fully operate the systems, and therefore operation and maintenance problems start to emerge.

(9) Operation and maintenance manuals: During the visits performed in this study, it was identified that another typical problem is the lack of operation and maintenance manuals. In several WWTPs (such as those in Panajachel and Santa Cruz), no manuals are available and therefore, without a guide, the operation of WWTPs is complex.

(10) By-products: During the inspection visits, it was recognised that, in all cases, WWTPs lack solutions to handle the produced sewage sludge and biogas. On the one hand, for sewage sludge, WWTPs count on treatment units to dehydrate the sludge, however, stabilisation units are frequently missing (only WWTPs in Panajachel, Santa Catarina, and San

Marcos include sludge digesters). Additionally, there are no safe and clear solutions as to how to dispose of or use the treated sludge. On the other hand, the biogas generated during anaerobic wastewater treatment or sludge treatment is only burned, and no energy recovery is achieved. As an exception, the WWTP of San Bartolo in Sololá produces biogas in anaerobic wastewater reactors, which is later sent to nearby households where it is used for cooking purposes.

(11) Flood areas: Some WWTPs are located in high risk flood areas. For example, the WWTP at San Marcos is situated in an area that is highly susceptible to floods (Susana Heisse, personal interview, June 5, 2017). The same applies to the WWTP at Panajachel, where the land it is located on has already been flooded before. In 2010, due to a strong hurricane, the WWTP was completely destroyed (Genaro Umul, personal interview, May 29, 2017).

3.5.2 Potential Solutions

Potential solutions for the current O&M problems of WWTPs located at Lake Atitlan include possible management and technical improvements. In Figure 13, the identified issues have been mapped to potential solutions.

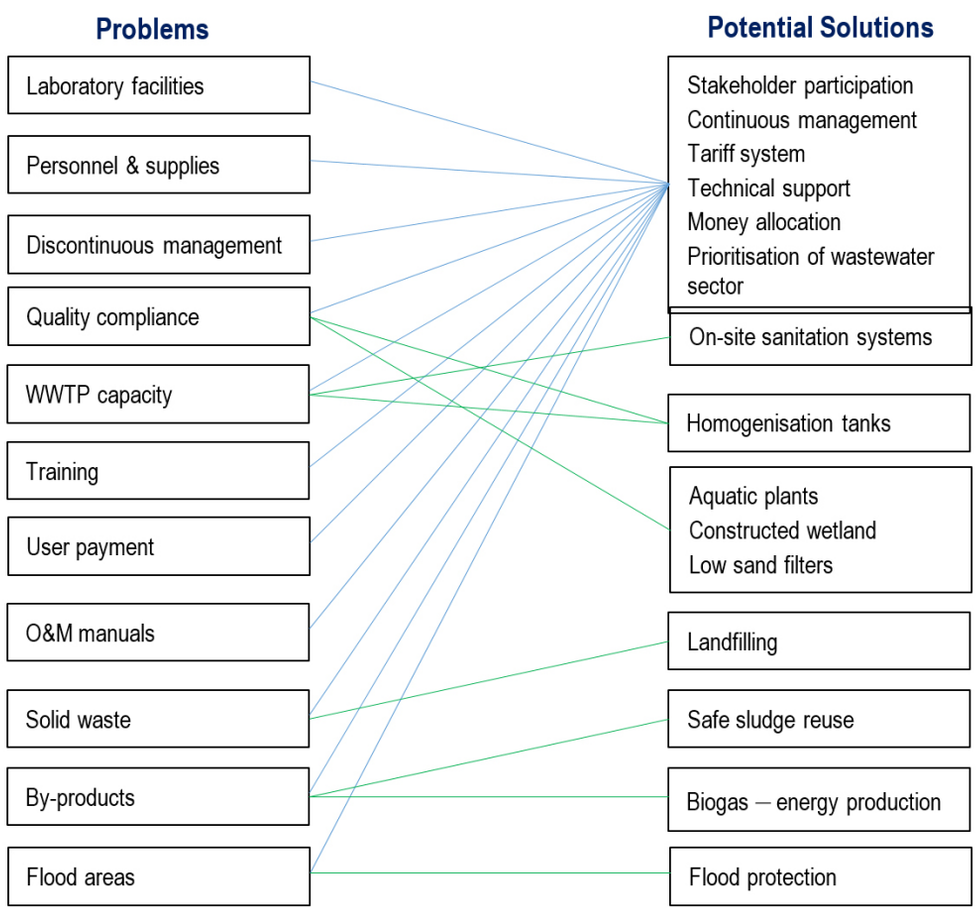

Figure 13: Identified operation and maintenance problems at WWTPs mapped to potential solutions

For all matters, prioritising wastewater management in the region can be essential to attract more global attention and resources. Promoting stakeholder participation can also contribute towards engaging main actors, drawing more attention to the current wastewater management problem, and facilitating the decision-making process through consideration of all stakeholders' opinions. It is also essential to work on establishing new policies where a change of governments does not radically affect wastewater management in the regions. Additionally, more potential actions include increasing technical support for municipal and private WWTPs (potential training on proper O&M practices, by-products handling, monitoring, and other technical affairs) and allocating more monetary resources to ensure adequate supply of reagents, personnel, equipment, and electricity. Finally, it is fundamental to start a new tariff system to make systems more affordable. New mandatory compliance policies need to be created to establish a new tariff system.

This study also suggests potential technical solutions for problems of WWTP capacity, quality, by-products, and for flood risk areas. First, the amount of adequately treated wastewater can be increased by expanding on-site sanitation systems and by incorporating homogenisation tanks at the entrance of the WWTPs. With homogenisation tanks, water can be stored and sent at a constant rate to the WWTP. Therefore, maximum capacity can be harnessed at all times. Second, for wastewater quality problems, this study suggests considering the integration of technologies such as the use of aquatic plants, constructed wetlands, or low sand filters. Moreover, homogenisation tanks can also remedy the problems of quality since equalisation also occurs for the quality of wastewater and hence it is possible to avoid high concentration peaks. Third, for WWTPs located at areas prone to floods, it is advisable to put in place measures such as physical barriers. In the future, it is not recommended to place WWTPs in this type of areas. Fourth, WWTPs urgently require by-product handling plans. Practices of burying garbage should be stopped and replaced by appropriate landfilling disposal. For sewage sludge, correct stabilisation methods (such as composting or liming) should be implemented to reduce the microbial load. After treatment, it is possible to use sludge as fertiliser, soil conditioning, material for construction supplies, or it has to be incinerated. Finally, biogas can be employed to generate electricity and reduce the energy consumption from WWTPs.

4. Major Findings: A Summary

In the region of Lake Atitlan, both off-site and on-site sanitation systems are used to dispose of faecal material and urine. In summary, off-site systems receive excreta from 55% of the basin population while 44% of the population use on-site facilities (such as septic tanks, latrines, or soak pits). Information regarding maintenance is missing, and therefore it is not possible to determine if the faecal material is being safely handled. Finally, presumably 1% of people continue practising open defecation. Summarising the situation, it can be inferred that, currently in the region, most of the faecal sludge is not safely managed. As a consequence, the environment can be severely affected. It is necessary to take efforts to not only increase the capacity and improve the performance of WWTPs but also to promote safe practices for on-site sanitation systems (such as regular desludging and safe handling of faecal sludge).

The community in the basin of Lake Atitlan produces 45,500 m^3 of wastewater per day, and 12 WWTPs are available in the region. The current capacity of all WWTPs is approximately 10,400 m^3 per day. Therefore, only around 20% of sewage produced in the catchment can be treated. The most common technologies inside the WWTPs are activated sludge and a combination of anaerobic reactors and biological percolating filters. Treated wastewater has different disposal routes like crop irrigation, discharge into the lake of its tributary rivers, and land infiltration. Untreated wastewater is discharged into rivers, directly into the lake, or infiltrated in open grounds.

Moreover, for the available WWTPs in the Lake Atitlan basin, quality problems are frequently present. Pathogens and nutrients are rarely removed and additionally, although COD, BOD, and TSS have medium to high removal rates, the local thresholds are still not met. In the region, due to the nature of the lake (endorheic lake where the water retention time is approximately 80 years), stringent quality thresholds are included in the local regulation. Current WWTPs only include conventional treatment technologies such as (1) traditional activated sludge (with a retention time of less than 8 hours) and (2) combination of anaerobic reactors with percolating filters. Such technologies remove organic matter and suspended solids but not at a sufficient rate. Therefore, to meet the local legislation, new techniques to eliminate pathogens and nutrients and polishing technologies for suspended solids and organic matter may be implemented.

Concerning the operation and maintenance bottlenecks, the Lake Atitlan region faces several problems. Mainly, the identified issues include the lack of laboratory facilities, constant technical training, handling plan for by-products, personnel and supplies, operation and maintenance manuals, and willingness to pay for users. Similar issues have also been reported for other LAC countries. According to Cossio et al. (2017), in small Bolivian cities, the available WWTPs are also commonly malfunctioning systems. The failure is related to factors similarly reported in the case of Lake Atitlan: lack of access to O&M manuals, monetary resources, willingness from people to pay for wastewater treatment services, training, and monitoring. Thus, it can be presumed that a similar situation is

occurring in other areas of LAC. In the future, more sustainable approaches should be adopted in the selection of wastewater treatment strategies. The selection process should avoid making decisions based only on initial conditions and investment costs. It is necessary to actively evaluate O&M conditions along with more social and environmental parameters to achieve real sustainable systems.

As a final remark, activated sludge plants present more O&M problems than anaerobic-percolating filter plants. Activated sludge plants show higher O&M cost, require more personnel and more skilled knowledge to operate the facilities. Evaluating the local conditions, where not enough financial resources and trained staff are available, for the study area, it is recommended that the selection of activated sludge technology for future WWTPs be reassessed.

Lastly, the main limitation of this study was data scarcity. No clear information about wastewater management is available in the region. Besides, for existing data, information is not up-to-date, and different sources report inconsistent facts. Additionally, crucial information (such as wastewater generation) is missing, and only rough estimations are available. It is recommended to involve all main stakeholders in the region to improve the accuracy of the data presented in this report. Data should be analysed and compared with other possible existing sources. Moreover, the second limitation of this study was time constraints; during the field visit, only five WWTPs were visited. However, to overcome the limitations, main stakeholders with knowledge about all WWTPs were interviewed to capture a bigger and better picture of the situation of the whole region. In the future, other WWTPs can be consulted to verify the results of this study.

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