Faecal Sludge Management in Urban On-site Systems

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Abstract: Faecal sludge management is a fundamental activity for the adequate operation of on-site sanitation systems. Currently, this management is often overseen in developing countries, which can result in severe consequences to public health and the environment. The present dissertation aims to study the several processes of the cycle of faecal sludge management in urban areas of developing countries. The knowledge gained is applied to a case study of the City of Tete, in Mozambique. A description of the main types and challenges of sanitation systems of developing countries are briefly presented and discussed. The technical solution of the processes of collection, transport, treatment and alternative final destination of faecal sludge are described. Additionally, a preliminary design of a Sludge Treatment Plant, integrated in a faecal sludge management system, is carried out for the urban centre of the City of Tete. The urban structure is analysed and a treatment solution is proposed for the city's faecal sludge and sewage.

Keywords: Wastewater, faecal sludge management, developing countries, on-site sanitation systems

1. Introduction

Adequate management of faecal sludge, from local sanitation systems, is essential to prevent negative consequences to public health and the environment. Currently, around 2.7 billion people depend on local sanitation systems, with a prediction to reach 5 billion people in 2030 (Strande, et al., 2014). These are the dominating sanitation systems in developing countries, where urban centres are typically dominated by large population growth which results in high occupation densities, thus presenting the most significant challenges for faecal sludge management. It is considered the need for this activity in urban centres that have more than 150 inhabitants per hectare, requiring with that require the collection, treatment and disposal of faecal sludge from on-site systems far from its origin point.

Faecal sludge management is a broad and complex topic, involving technical, logistical, financial and regulatory aspects, with several local variants. Thus it is essential it is crucial to have knowledge of all stages and be aware of the main challenges, to ensure long-term operation of on-site systems. In addition to this factor, there are many stakeholders involved in planning and operation of the system. This dissertation results from an extensive research on the most recent documents on faecal sludge management, with application of the knowledge apprehended to the case study of City of Tete in Mozambique, where a Faecal Sludge Treatment Plant is designed.

2. Faecal sludge systems

2.1.1. Characterization of faecal sludge

Faecal sludge is the generic term given to fresh or only partially digested slurry or solid material that results from storage or treatment of excreta mixture of black and water, with or without addition of gray water from storage of local sanitation systems. The parameters for analysis of faecal sludge are the same used for sludge from Wastewater Treatment Plants (WWTP), which include pH, total solids, electric conductivity, *Kjedahl* nitrogen, C/N and BQO/COD ratio, faecal coliforms and Helminthes eggs. Although the parameters are the same, the differences between these two types of sludge must be taken into account: faecal sludge generally contains higher concentrations of suspended and dissolved solids and concentrations of pathogenic microorganisms, also presenting greater resistance to stabilization and dehydration (USEPA (1999), in Strande et al. (2014)). The characteristic of faecal sludge are highly variable, depending on toilet technology and usage, storage duration, local climate, collection method and inflow and infiltration from the environment into the system (Strande, et al., 2014).

In recent years there the concept of sustainable sanitation has been developed, i.e., a set of infrastructure and services economically feasible, socially and technically acceptable, with institutional appropriateness, promoting public health and protecting the environment and natural resources. The main goals to achieve sustainable management of faecal sludge are: recovery of nutrients; removal of pollutants; increase concentration of nutrients; sanitize the faecal sludge for reuse and implementation of economic and energy efficiency, demand-driven resulting products (Drechsel, et al., 2010).

2.1.2. Categorization of faecal sludge systems

Faecal sludge systems are considered to involve the sanitation systems and manner of management of the faecal sludge resulting from these systems. The sanitation systems can basically be divided into **wet** or **dry** systems, depending on the amount of water used (due to the water access and capitation of the household), influencing sludge characteristics and digestion.

The designation of on-site or off-site depends on the location where resulting sludge is managed. **On-site sanitation** refers to when collection, storage, treatment/dehydration and disposal of effluent and/or excreta occur mostly within or near their origin. In the present dissertation, a designation of **semi-on-site sanitation** is given for on-site systems that after a certain period of time require the collection, treatment and disposal of the sludge away from its origin, which occurs mainly in dense urban centres. On-site systems are the most common type of sanitation in developing countries, specifically in sub-Saharan Africa system where 65-100% of sanitation in urban areas is provided by such systems (Dodane, et al., 2012). These are not considered adequate for density above 150 inhabitants per hectare, as the infiltration of the effluent is not safe. **Off-site sanitation** implies the storage and treatment of sludge away from its origin and usually resort to a sewage network of collectors and/or mechanical transport of sludge. These systems are used by about 90% of the population of developed countries.

Finally, regarding the location and usage of infrastructure for treatment, there are **centralized**, **decentralized** and **semi-centralized** systems. The **centralized** systems rely on normally in infrastructure with large capacity, where the treatment is carried out from various exudates housing in only a treatment site, considered suitable for high water capitations for densities from 150 to 600 inhabitants/hectare (Alaerts, et al., 1990). The **decentralised** (DEWATS, Decentralised wastewater systems technology) refer to small-scale systems, including collection, treatment and discharge of wastewater, suitable for the treatment flow rates between 1 and 500 m^3/day (Sasse, 1998). The **semi-centralized** systems emerge as an intermediate solution between these two systems, dividing the treatment process into smaller treatment units. The treatment plants may be connected to a sewage network or integrated in faecal sludge management system technology with greater capacity and generally technologically more advanced than purely decentralized systems (Tilley et al. , 2014).

2.1.3. Main challenges in faecal sludge management

Sanitation and consequent management of faecal sludge exists both in urban and rural settings, with different challenges each one. In **rural** areas the management of sludge technological solutions are not generally problematic, being a small and relatively cost efficient and secure use simple technologies such as dry sump drainage ('leaching pit latrines') and there are natural large areas available for absorbing the pollution loads. Problems in rural areas are related to the financially aspects and cultural acceptance of technological solutions. In **urban** settings however, the increasing population density characteristic of developing countries, results in high amounts of sludge that deplete the natural assimilative capacity of nature and the available space for treatment and final disposal becomes scarce and expensive, challenging the choice for local sludge management solutions. When sludge management is not efficient it can result in serious environmental and public health consequences (Alaerts, et al., 1990).

The management of faecal sludge is a complex process involving several variants and participants, which can be divided in four main themes (Strauss & Montangero, 2002): (i) **technical** aspects, mainly related with the solutions and technological problems that arise during the collection, processing and transport of faecal sludge, for example due to difficult accesses and traffic; (ii) **legislative** aspects, that are essential to provide necessary tools and ensure a participatory and responsible for fulfilling its function approach, in accordance with the laws and established policies, promoting sustainable sanitation; (iii) **financial and economic** aspects to enable the development of faecal sludge systems, especially important in developing countries as most depend on funding from foreign countries and organizations to implement (Strande et al., 2014) and (iv) **socio-cultural** aspects, fundamental to ensure the long-term adequate operation of faecal sludge management through integrated planning that includes the participation and coordination of the stakeholder, where it is crucial to define the roles and responsibilities as well as understand the interests, needs and limitations of each of party.

2.2. Technical solutions of faecal sludge management

2.2.1. Collection and transport

The cycle of faecal sludge begins with the collection of sludge from the semi-on-site sanitation systems, which can be done manually or mechanically. **Manual collection** of faecal sludge is most often used due to low cost and difficult of access to the sanitation system, done by spades and buckets, often with the individual within the pit. The creation of equipment to assist the worker in manual collection of sludge is arising. M**echanical collection** is more efficient able to remove larger volumes of sludge faster with little direct exposure to sludge, reducing health risks. This technology is generally expensive and prone to mechanical failure.

The transportation of sludge is made by 'low cost', standardized or adapted equipment, which may be manual or motorized. The manual transport is generally equipment pushed by a worker that transports containers of faecal sludge, generally with low capacities and speeds, not suitable for distances higher than 500 meters. Motorised transport refers, in general, moved by a motor vehicle, with higher capacities and speeds but with higher costs suitable for less than 3 km (WaterAid, 2013).

2.2.2. Transfer stations

Most of the transport equipment described above are of small size and only suitable for short distances. Furthermore the treatment and unloading locations suitable for faecal sludge generally are situated in the periphery of cities, implying long distances. Transfer stations arise as a solution of the "decentralized" type, which is based on intermediate but easily accessible premises, considering appropriate the use of a transfer station when the transport of faecal sludge for distances over 3 km is required. There are two phases for the operation of transfer stations: primary transport, where the smaller equipment carries the sludge from its origin to the transfer station and a second phase, when the transfer station if full and equipment with higher capacity, such as trucks and storage tanks, collects the sludge and transports it to the treatment facility. Transfer stations can be fixed or mobile. The **fixed stations** are intended for permanent storage and are subdivided into four categories**:** permanent storage tanks; modular transfer station, with portable storage containers that can hold various sizes; multifunctional storage tank, that can provide treatment of the sludge; and network-attached station, that have direct or indirect connection to the sewage network.

The **mobile stations** are portable containers, for temporary storage and easily transportable. The container may be a motorized vehicle or storage trailer with a tank that, when needed, are pulled by a truck or tractor. The main advantage of the provisional nature is that is overcomes problems of many logistical procedures required needed to install the fixed transfer stations, especially in areas of high population density. Furthermore, if necessary, these stations can also be used as secondary transport, transporting the sludge to the treatment site. These stations can also be provisionally used to test the location of a fixed transfer station.

2.2.3. Treatment/dehydration solutions

The main goal of treatment of faecal sludge is to ensure public health and protect the environment through the reduction of pathogenic microorganisms and the stabilization of organic matter and nutrients. The dehydration of faecal sludge consists on the removal of water from sludge, a fundamental process to reduce the sludge volume and weight, reducing the cost of transportation and final treatment. The resulting products generally need further treatment and/or storage. The selection of technologies to choose and combinations thereof depends on the location, characteristics of the sludge, final destination and legislation.

The **mechanical dehydration** is used in WWTP and have only been a few times used for faecal sludge being the main four mechanical equipments: belt filter, centrifuge, frame filter press and screw press. The **settling tank** is also a solid-liquid separation process that relies on gravity for the sedimentation of sludge with a settling efficiency of the suspended solids between 50- 60% to 80%.

Unplanted drying beds present a simple and effective process for the dehydration of sludge. It consists of a shallow filter media consisting of sand and gravel where sludge is laid, applied of layers of 20-30 cm, and has a drain at the bottom to collect the effluent. The duration of the drying cycle may vary, being generally on the order of 5 to 20 days, varying with the local climate and the loading rate of total solids (Strauss & Montangero, 2002). The loading rate varies according to local conditions, it is possible to define a range between 100 and 200 kg ST/(m^2.year) for tropical climates. The leaching of effluent results in a reduction in volume of sludge from 50 to 80%, varying with the characteristics of faecal sludge. The final dried sludge total solids concentrations are between 25 and 70% according to the loading rate rate and retention time. The dried sludge from drying beds can be used as fertilizer or soil conditioner. In most cities, the sludge resulting from this technology require further storage and subsequent drying in the sun to have hygienic quality for use without restriction (Strauss & Montangero, 2002). It is advisable to store sludge for periods up to one year to take place reduction of pathogenic microorganisms, and the treatment of wastewater in the impoundment systems (Strande, et al., 2014).

Planted drying beds similar to the single bed drying, it differs by the existence of *macrophytes* plants, higher volumes and bed depths, and not requiring the removal of sludge at the end of each drying cycle. The treatment processes that occur in this treatment include dehydration, mineralization and stabilization of faecal sludge. The dehydration efficiency in tropical climates leads to dry matter percentage higher than 30%. **Co-composting of faecal sludge** is a treatment that consists of a biological process of decomposition of organic matter by microorganisms under aerobic conditions, with destruction of pathogenic microorganisms due to the high temperatures reached in the exothermic process (60-70ºC). This process results in a "compost of great value as an organic fertilizer. Some important parameters to control in this process are the ratio of carbon and nitrogen, the oxygen concentration, moisture and the particle size. **Lime addition** has been tested in developing countries, for stabilization of organic matter, reduction of pathogenic microorganisms, heavy metals and phosphorus. It consists in mixing forms of lime to raise the pH to 12 or 13.

The **stabilization pond system** consists of a set of ponds with different characteristics and depths often used for wastewater treatment and capable of performing co-treatment with faecal sludge. There are three types of ponds, anaerobic pond, and aerobic or facultative pond maturation pond, which may be used individually or in series, with the highest treatment efficiency obtained with each type of pond in series. In the **anaerobic pond** there is sedimentation of solids and BOD removal of 60 to 70%, with retention times between 1 and 7 days and depths between 2 and 5 m. Sludge removal is necessary generally between 2 and 5 years, depending on the rate of accumulation of sludge per inhabitant, which varies between 0.03 and 0.1 m^3/(inhab.year), depending on local climate (Sperling & Chernicharo, 2005). The BOD affluent to the pond varies between 200 and 750 mg/L (Strande, et al., 2014). The **facultative pond** allows the settling of solids with anaerobic degradation and aerobic digestion at the top of the pond, promoted by natural wind. The BOD removal efficiency of anaerobic and facultative ponds in series is about 75% of BOD (Tilley, et al., 2014), and the BOD loading rate for the facultative pond varies between 240 and 350 kgCBO5/(ha.day) for warm regions. There are two main types of hydraulic systems to define pond regimes: plug-flow and complete mix, being some variations as the complete mix reactors in series and dispersed flow. For the design of facultative ponds the model of complete mix is frequently adopted due to its simplicity, and the dispersed flow for the determination of BOD. The **maturation pond** is intended for removal of pathogenic microorganisms achieving high efficiencies with depths between 0.5 and 1.5 meters, allowing penetration of sunlight and oxygen from wind aeration. The systems may of maturation ponds in series or one pond with baffles.

Some innovative treatments are currently being developed, amongst which the **Conversion of Organic Refuse by Saprophages (CORS)** that are organisms that feed on dead matter or decaying used for decomposing faecal sludge, two examples of this kind of treatment are vermicomposting and black soldier flies. **Treatment with ammonia** aims to reduce pathogen microorganisms, taking advantage the high concentration of ammonia present in urine. Finally **solar drying** is a dewatering technology applied in large scale in United States and Europe since the 19th century for sewage treatment, which dries the sludge in structures such "greenhouse" with passage of sunlight.

2.2.4. Disposal

The evaluation of alternatives for final disposal of sludge is a complex and sometimes costly process that is often overlooked as part of the design of the sludge management system. There are several alternatives for the final destination of sludge, such as oceans, sanitary landfill, reuse in agriculture and aquaculture, areas with lack of nutrients and waste lands organic matter, as mining areas (Sperling & Chernicharo, 2005), burial trench and storage (Tilley et al., 2014). Storage is an alternative for dried sludge that underwent treatment but has not reached the desired quality. Although this option is a disposal solution, information on the design is scarce. According to (WHO, 2006), for total inactivation of pathogenic microorganisms such as viruses, bacteria, protozoa and Ascaris eggs it is necessary storage for over one year at ambient temperatures above 20-35ºC.

3. Case study of City of Tete

3.1. Characterization of City of Tete

The Republic of Mozambique is a country in south-eastern Africa comprised of 11 provinces, including the province of Tete, northwest of Mozambique, of which City of Tete is capital. In Tete province large reserves of coal were discovered, attracting high investments from all around the world, which have encouraged the planning of the city as for the “Urban Development Plan for the City of Tete” (Conselho Municipal de Tete, 2011). The Zambezi River, one of the most important natural resources in Africa, divides the city of Tete in two. The City of Tete has a dry tropical climate characterized by high temperatures and medium/low humidity (Instituto Nacional de Estatística, 2013). The average temperature is 26.5ºC and the lowest average temperature of the year is 22 °C (Climate-Data, 2014).

The city of Tete extends approximately 30 km along the Zambezi River and approximately 15 km across. It is composed by nine neighbourhoods. Due to the high extent of area, with large rural areas with low population density and a division of the city due to the river, the case study is focused on the dense urban center, consisting of three neighbourhoods that represent 30% of the population of the City of Tete. These neighbourhoods are *Felipe Samuel Magaia*, *Josina Machel* e *Francisco Manyanga,* which are jointly called “Urban space”. It is located on the right bank of the Zambezi River, near the old bridge that connects the two banks. The Urban space is consolidated, characterized by a well defined building area with buried infrastructure and paved roads. On the west side of Urban Space there is a strip of land, called *Nhartanda* Valley, which is an easily flooded area. The urban density and disarrangement of the urban environment grows with the proximity to the Valley.

3.2. Methodology for selection of faecal sludge treatment solution

The methodology used in this case study was based on the literature review conducted, taking into consideration the main factors when choosing a sludge treatment solution in developing countries. The two main factors for City of Tete to choose the solution in study: the tropical climate and the availability of land. The system also should require low maintenance, simple construction and adequate technical solutions.

Different alternatives for dehydration/treatment were made according to the origin of the sludge to account its characteristics. The wastewater from the existing sanitation network is transported by an interceptor to the Faecal Sludge Treatment Plant (FSTP), where it is treated in a stabilization pound system of an anaerobic, facultative and maturation ponds in series. The sludge from septic tanks is transported by truck to a tank at the FSTP, with a capacity for storage of sludge for two days, to control the discharge of sludge into the drying beds. The untreated effluent from the dewatering of sludge is forwarded to the stabilization ponds. Finally, it is considered that the sludge from dry pits is collected and transported to transfer stations in the Urban Space and then transported by trucks to the FSTP. The sludge from dry pits is collected every two years, stabilized, with low water content. At the FSTP, the sludge is stored until they reach sufficient quality to final destination (for about 6-12 months). The FSTP is located south of the Urban Space, in a area with planed use for infrastructures for city development.

3.3. Design of the Faecal Sludge Treatment Plant

The design of the FSTP is done for the year 2030, presenting the estimated flow of sewage and sludge for the year 2045. The FSTP is inserted in a faecal sludge management system being essential to have Transfer stations.

The current total population of the City of Tete was estimated using equation (3.1) and the data from the 1997 and 2007 census, determining the geometric rate of population growth of 4.5% which is considered for estimation of the population for year 2015, reducing this value in half for 2030 and 2045 to account the natural tendency of reduction of fertility, obtaining the population for each horizon year presented in Table 3.1.

$$P_n = P_i \times (1 + t)^n \tag{3.1}$$

Where:
$P_n -$ Population in year n
$P_i -$ Population in year ano i
$t -$ Geometrical rate of population growth
$n -$ Year

Table 3.1: Population od Urban Space with geometric rate of population growth for the horizon years and

	Unit	2015	2030	2045
Total population of City of Tete	inhab.	224.260	262.840	366.300
Dist. population	%	30	50	68
Population Urban Space	inhab.	67.280	129.740	250.180

The current sanitation infrastructures of the Urban Space are a sewage network with 6 dischargers into the river Zambezi, as seen in Figure 3.1. The rest of the Urban Space relies on semi-on-site sanitation.

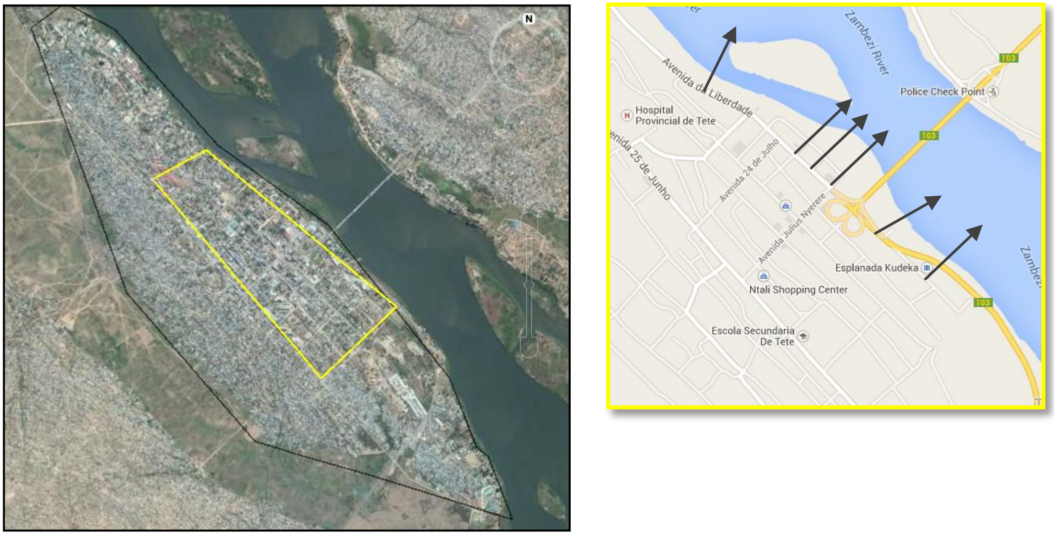

Figure 3.1: Delimitation of sewage network area and detailed location of the 6 sewage discharges of the Urban Space of the City of Tete.

Due to the lack of records of current situation of the on-site sanitation systems, in the present study the sanitation options of the Urban Space are simplified, considering that beside the sewage network, there are septic tanks and dry pits in the Urban Space, with the estimates of population coverage shown in **Table 3.2**.

Table 3.2: Population served by different types of sanitation system for project years of horizon.

	2015		2030		2045	
	Distribution	Inhabitants	Distribution	Inhabitants	Distribution	Inhabitants
Dry pit	82%	55.170	70%	90.820	60%	150.100
Septic tank	10%	6.730	15%	19.460	25%	62.550
Sewage network	8%	5.380	15%	19.460	15%	37.530

The determination of the sludge from each system is done considering 6 people per household and adopting a coefficient to take in account variable factors. For the dry pits, a coefficient of 50% is applied to the total number of pits of the Urban Space, to consider that some are true on-site systems and will not need to be collected. An average pit volume of 1.5 m^3 is adopted, assuming that 30% are solid waste, removed in pre-treatment, and a period between sludge collections of 3 years, considering 225 working days in a year. The sludge flow arriving to the FSTP is determined and presented in Table 3.3.

Table 3.3: Determination of sludge flow from dry pits, from the Urban Space, for each project horizon.

	Unit	2015	2030	2045
Inhabitants served by dry pit	inhab.	55.170	90.820	150.100
Nº inhabitants per dry pit	inhab.	6	6	6
Total number of dry pits	-	9.200	15.140	25.020
Dry pits to collect	%	50	50	50
Total number dry pits to collect	-	4.600	7.570	12.500
% of municipal solid waste	%	30	30	30
Total sludge volume	m^3	4.830	7.950	13.130
Period between collections	days	675	675	675
Annual sludge production	m^3/year	1.610	2.650	4.380
Daily sludge production	m^3/day	7	12	19

The determination of the septic tanks is done similarly, assuming an average volume of septic tank of 2 m^3 and a period between collections of 3 years. A coefficient of 66,7% is applied as only 2/3 of the septic tanks volume is collected to assure the proper operation and cleansing of the effluent. The results obtained are presented in Table 3.4.

Table 3.4: Determination of sludge flow from septic tanks, from the Urban Space, for each project horizon.

	Unit	2015	2030	2045
Inhabitants served by septic tank	inhab.	6.728	19.461	62.545
Nº inhabitants per septic tank	inhab.	6	6	6
Total number of septic tanks	-	1.120	3.243	10.424
Average volume septic tank	m^3	2	2	2
% volume to collect	%	66,7	66,7	66,7
Total sludge volume	m^3	1.500	4.330	13.900
Period between collections	years	3	3	3
Annual sludge production	m^3/year	500	1.440	4.630
Daily sludge production	m^3/day	2.2	6,4	20,6

The population for the determination of the sewage flow corresponds to the population with access to piped water considered to be the population served by the sewage network and septic tank, corresponding to 18% of the Urban Space population in year 2015. In coordination with the *Fundo de Investimento e Património de Abastecimento de Água of Mozambique (FIPAG)* ('Heritage Fund and Water Supply') the values of the annual volume of water supplied and the maximum daily consumption were obtained, from which we calculated the average daily consumption values, presented in Table 3.5.

Table 3.5: Values of annual volumes of water supplied and maximum and average daily intakes.

	Unit	Flow
Annual volume of water supplied	m^3/year	2.538.000
Maximum daily consumption	m^3/day	16.730
Average daily consumption	m^3/day	7. 960

Initially the capitation for year 2015, using the results of Table 3.5, assuming a water loss of 30%, resulting in a capitation of 120 L/(inhab.day). From this value the capitation for 2030 and 2045 is estimated to be 150 L/(inhab.day). The average daily flow rates are estimated for the population connected to the network of collectors, using equation (3.2), considering the influx factor to the network 0.8.

$$Q_m = Cap \times Pop \times Kr \tag{3.2}$$

Where:

$Q_m - Average\ daily\ flow\ (L/dia)$

$Cap - Capitation\ (l/(inhab.dia)$

$Pop - Population\ (inhab)$

$K_r - Influx\ coeficient$

The calculation of peak flow rates was made affecting the daily average flow for instant factor calculated by the expression (3.3). The values obtained for the calculation of domestic design flow for the design horizons are presented in Table 3.6.

$$F_h = 1.5 + \frac{60}{\sqrt{Pop}} \tag{3.3}$$

Where:

$Pop - Population\ connected\ to\ sewage\ network$

$f_p \leq 5$

Table 3.6: Determination of domestic flows.

	Unit	2015	2030	2045
% inhabitants served by sewage network	%	8	15	15
Inhabitants served by sewage network	hab.	5.380	19.460	37.530
Capitation	l/(inhab.day)	120	150	150
Influx coefficient	-	0,8	0,8	0,8
Average daily flow	l/day	519.120	2,335.280	4.503.250
Instant factor	-	2,32	1,93	1,81
Peak flow	m^3/day	1.200	4.500	8.150
Peak flow	l/s	14	52	94

The transfer stations should be able to receive the faecal sludge from latrines. It is considered that the coverage of a transfer station corresponds to a radius of 1 500 meters, to account the irregular streets, complying the theoretical limits of up to 3km to collection transport. For the choice of the implantation sites the mesh of urban space is analyzed, looking with good access routes for trucks and coverage for the entire area with semi-on-site sanitation.

It is proposed that the stations containers be modular type, having the advantage of being easily transported for repair, cleaning or for direct transport to the ETL. To avoid unpleasant odours and discomfort to the community, the containers are in closed structures in a closed permanent structure, with appropriate access to the discharge and collection of sludge. Moreover, the stations must have pre-treatment, in the form of bars/network. The location and coverage of the two transfer stations are shown in Figure 3.2.

It is considered that the sludge taken from latrines, after a storage period of three years, present a content of 60% (Bakare, et al., 2012) water presenting semi-solid compound properties. Assuming the trucks used have a capacity or around 8 m^3, it is necessary one truck to perform two unloading of each transfer station. The transfer station consists of two standard waste containers of 6 m^3 capacity, occupying an area of approximately 15 m^2 (4 x 1.9 m). An area of 100 m^2 (10 x 10 m) is adopted for each transfer station to account space for equipment and passage.

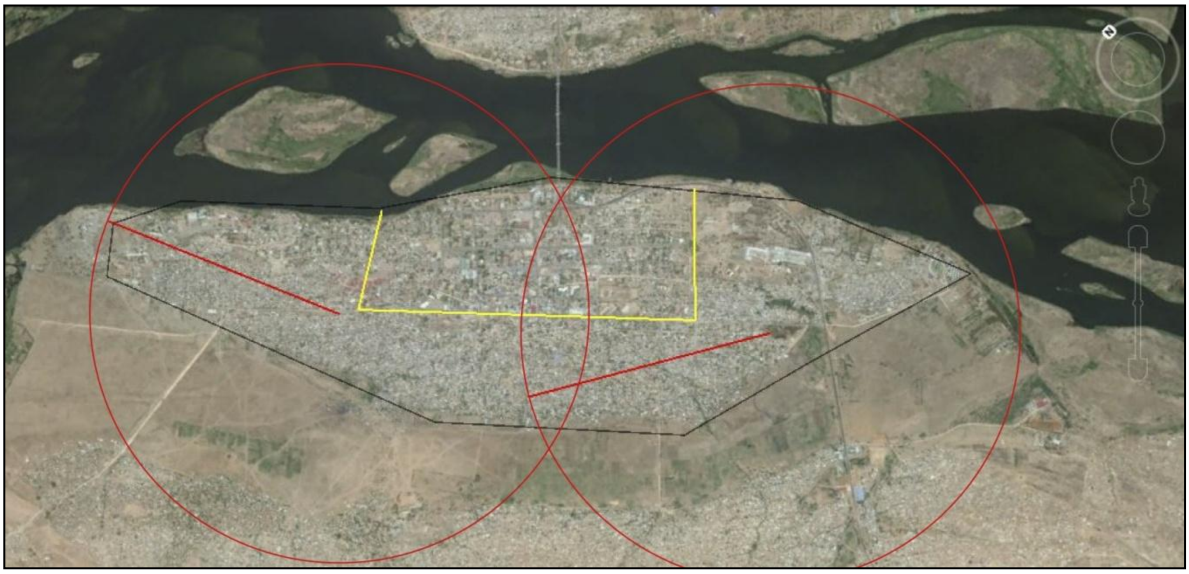

Figure 3.2: Location of the transfer stations with a 1500 meters radius for the area with semi-onsite sanitation of the Urban Space.

Unplanted drying beds

The sludge from septic tanks is transported directly to a tank at the FSTP with storage capacity for two days, which reflects in a volume of 13 m^3. A tank of 2x5 m with a 1.5 m height is adopted. For the design of the drying beds, the minimal area required is determined for a layer of 20 cm of sludge deposited which for a daily flow of 6,4 m^3 results necessary a 32 m^2/day. The annual load of sludge discharged is determined through equation (3.4):

$$M = c_i \times \mathrm{Q_i} \times t \tag{3.4}$$

Where:
$\mathrm{M} -$ Faecal sludge load (kg ST/ano);
$c_i -$ Average concentration of total solids (g ST/L);
$\mathrm{t} -$ Number of days sludge discharged

Adopting an average concentration of 30 TS/L (approximately 3%), the mass of total solids per year, equation (3.4) results in 43 250 kg. With this value and adopting a loading rate of total solids of 200kg TS/(m^2.year) it is concluded that an minimal area of 215 m^2 for sludge drying is needed. It is proposed 8 drying beds, with an area of 32 m3 (4x8 m), with a drying cycle of 8 days, theoretically achieving a solid content of around 40%. The filter constitution of the drying beds is presented in Table 3.7, according to (EAWAG & Spuhler, 2014). To determine the accumulated sludge from the drying beds, it is considered that the influent sludge has a composition of 3% dry matter and that the dry sludge has 40% of dry, resulting in a 108 m^3 of dehydrated sludge per year.

Table 3.7: Characterization of the filter medium of drying beds.

Layer order	Material	Diameter (mm)	Thickness (cm)	Adopted dimension (cm)
1	Fine sand (local)	0.1 to 0.5	25 to 30	30
2	Thinner gravel	5 to 15	10 to 15	15
3	Gravel	20 to 40	20 to 30	25
			Extra wall height	30
			Total height	100

Stabilization ponds

For the design of the **anaerobic pond** the total BOD affluent to the pond, from sewage network, is determined. Assuming a load of 60 g BOD/(inhab.day) for the capitation of 120 L/(inhab.day) results a load of 500 mg BOD/L, which for the average daily flow results a 1170 kg BOD/day. A volume loading of 0.3 kg BOD/(m^3.day) is adopted due to local high temperature from which the minimum volume and retention time are obtained. By defining a depth of

5 m and two anaerobic ponds, it is concluded that it is necessary to have a minimal of 390 m2 for each pond. The dimensions of each pond proposed are 15x30 m, with a height of 5 m, and a retention time of 3 days.

The BOD removal efficiency is calculated by equation (3.5), adequate for when the average temperature of the coldest month is between 10 and 25ºC. Applying this efficiency to the influent total BOD load of 1170 kg BOD/day the total load of 420 kg BOD/day for the effluent of the anaerobic ponds is obtained.

$$E = 2T + 20 \tag{3.5}$$

Where:
$E - \text{BOD removal efficiency}(\%)$;
$\text{T} - \text{Average temperature of the coldest month of the year (ºC)}$

Finally the amount of accumulated sludge from the anaerobic lagoon is calculated. An annual rate of sludge accumulation per capita of 0.03 m^3 is defined due to the tropical climate of the City of Tete. From this value the annual accumulation for the population of the Urban Space served by septic tanks is calculated, as well as the sludge layer thickness of both ponds. From these values the sludge removal cycle is determined. The accumulated sludge in anaerobic ponds must correspond to 1/3 of the ponds volumes, concluding that is necessary to remove about 1150 m^3 every 3 years. The main information regarding the design of the two anaerobic ponds are presented in Table 3.8.

Table 3.8: Main results and parameters for the design of the two anaerobic ponds of the FSTP.

	Unit	2030		Unit	2030
BOD volumetric load	kg BOD/(m^3.day)	0,30	BOD removal rate	%	64%
Minimal area each pond	m^2	390	Effluent's BOD	kg BOD/day)	420
With of each pond	m	15	Sludge accumulation rate per capita	m^3/(hab.year)	0,03
Lengh	m	30	Pop. served by sewage network	hab.	19.460
Area per pond	m^2	450	Total sludge accumulation rate	m^3/year	584
Depth	m	5	Collection period of accumulated sludge	years	3
Retention time	days	3	Sludge volume to collect every 3 years	m^3	1,300

The design of the **facultative ponds** requires the definition of the daily BOD load, defining 300 kg BOD/(ha.day) due to the hot climate and high solar radiation. The BOD from the effluent of the anaerobic ponds will be the influent of the facultative ponds. From these two parameters a minimal area of 14 000 m^2 is needed for treatment. Two facultative ponds are adopted to be coherent with the anaerobic ponds. Each pond has 1,8 m depth and is 50x150 m. The accumulated sludge is not significant, being of 32% by year 2030.

To determine the BOD and its removal efficiency, it is considered that the facultative ponds follow a complete mix model. The removal coefficient used is 0.27 (Von Sperling (2001), in (Sperling & Chernicharo, 2005)) which is adapted to the local average temperature of 26.5ºC through equation (3.6).

$$K_T = K_{20} \times \theta^{(T-20)} \tag{3.6}$$

Where:
$K_T - \; BOD\ removal\ coefficient\ for\ a\ temperatura\ T\ (d^{-1})$
$K_{20} - \; BOD\ removal\ coefficient\ for\ a\ temperatura\ 20ºC\ (d^{-1})$
$T - Temperature\ (ºC)$
$\theta - \; Temperature\ coefficient(-)$

The concentration of the soluble BOD of the facultative ponds effluent is determined using equation (3.7), adopting a 11 day retention time, obtaining a effluent of 84 kg BOD/day (soluble).

$$S = \frac{S_o}{1 + K \times t} \qquad (3.7)$$

Where:

S – BOD total concentration of the effluent (mg/L);
$\mathrm{S_o}$ – BOD soluble concentration of the effluent (mg/L)
K – BOD removal coefficient ($\mathrm{d^{-1}}$)
t – Retention time (d)

To estimate the particulate component of the effluent BOD of facultative pond, it is considered that 1 mg SS/L generates about 0.35 mg/L of BOD. Assuming that the effluent pond has a suspended solids concentration of 80mg/L, it is concluded that particulate component corresponding BOD is 28 mg BOD/L, resulting in a particulate concentration of the effluent of the facultative ponds of 65 kg BOD/dia. The total BOD of the effluent is the sum of the particulate and soluble component, resulting in 149 kg BOD/day, equivalent to a 64% efficiency of BOD removal. The facultative also removes faecal coliforms, considering a dispersed flow hydraulic regime. Initially the dispersion number is calculated through equation (3.8)..

$$d = \frac{1}{(L/B)} \qquad (3.8)$$

Where:

d – Dispersion number (–);
L – Pond length (m);
B – Pond width (m)

The bacterial decay coefficient is calculated using equation (3.9) for 20ºC, adapted to 26.5ºC by expression similar to equation (3.6) with a temperature coefficient of 1.07.

$$K_b = 0.542\, H^{-1.259} \qquad (3.9)$$

Where:

K_b – Bacterial decay coefficient for 20ºC(–);
H – Depth (m)

The concentration of faecal coliform of the ponds effluent is determined through expressions (3.10) and (3.11), assuming that the influent has $1\mathrm{x}10^7$ FC/100ml and a retention time of 11 days. From the values obtained determines the efficiency of removal of facultative ponds coliforms. The main results obtained for the maturation pond design are presented in Table 3.9.

$$N = N_o \frac{4\, a\, e^{1/2d}}{(1+a)^2\, e^{a/2d} - (1-a)^2\, e^{-a/2d}} \qquad (3.10)$$

$$a = \sqrt{1 + 4\, K_b\, t\, d} \qquad (3.11)$$

Where:

N_o – Influent faecal coliforms concentration (org/100mL);
N – Effluent faecal coliforms concentration (org/100mL);
$\mathrm{K_{bt}}$ – Bacterial die off coeficient for temperature T ($\mathrm{d^{-1}}$);
d – Dispersion number (–);
t – Retention time (days)

Table 3.9: Main results and parameters for the design of the two facultative ponds of the FSTP.

	Unit	2030		Unit	2030
Average daily flow	$\mathrm{m^3}$/day	2.340	Coeficiente de mineralização (26,5ºC)	$\mathrm{d^{-1}}$	0,3
BOD loading rate	kg BOD/ha.day	300	Effluent total BOD	kg BOD/day	149
Number of ponds	-	2	BOD removal efficiency	%	64%
Retention time	days	11	Die off coefficient (26,5ºC)	$\mathrm{d^{-1}}$	0,40
Depth	m	1.8	Influent faecal coliforms	FC/100ml	$1{,}0\mathrm{x}10^7$
Width	m	50	Effluent faecal coliforms	FC/100ml	$7{,}2\mathrm{x}10^5$
Length	m	140	FC removal efficiency	%	93
Area per pond	$\mathrm{m^2}$	7.000			

For the FSTP a **maturation pond** with baffles is adopted with a retention time of 16 days and a depth of 1 meter. Using these values and the average daily flow and minimal area of 28 .740 m^2 is needed. A ratio of 1 with length of 170 meters is chosen for the pond. Three baffles are proposed, dividing the pond in 4 internal spaces, which's equivalent ratio is determined by empirical equation (3.12).

$$L/B = \frac{L}{B}\,(n+1)^2 \qquad (3.12)$$

Sendo:

$\mathrm{L/B} -$ Equivalent ratio of internal divisions $(-)$
$\mathrm{L} -$ Pond length(m)
$\mathrm{B} -$ Pond width(m)
$\mathrm{n} -$ Number of internal divisions

The effluent from facultative lagoons is the influent for the maturation pond. The final concentration of faecal coliforms is determined the same as for the facultative ponds, resulting in a final concentration of approximately 600 FC per 100 ml. The maturation pond has a coliform removal efficiency of 99.92%, and the joint efficiency of facultative ponds and maturation pond is 99.99999%. The main results obtained for the maturation pond design are presented in Table 3.10.

Table 3.10: Main results and parameters for the design of the maturation pond of the FSTP.

	Unit	2030		Unit	2030
Number of ponds	-	1	Dispersion number	-	0,06
Retention time	days	16	Die off bacterial coefficient (26,5ºC)	d^{-1}	0,84
Average daily flow	m^3/day	2.340	Influent faecal coliform	FC/100ml	7,2 x10^5
Length	m	170	Effluent faecal coliform	FC/100ml	7,2 x10^2
Width	m	170	Maturation coliform removal efficiency	%	99,90
Total area	m^2	28.900	Maturation+facultatives coliform removal efficiency	%	99,99999
Number of baffles	-	3			
Equivalent ratio (L/B)	-	16			

Dehydrated sludge storage

Information for the dimensioning of the sludge storage is scarce, only with references to retention times and conditions for achieving faecal sludge quality. In the present case study the dehydrated sludge from dry pits and drying beds are stored in a covered area in the FSTP for at least 1 year. The minimum area required to implement the sludge storage for 1 year is determined with the flow of dehydrated sludge's assuming a sludge storage height of 1.5 meters, being necessary a minimum area of 2.130 m^2. An area of 2.800 m^2 (40x70 m) is reserved for the sludge storage.

The location of the wastewater and sludge treatment station is presented in Figure 3.3, with a total area of 6.65 ha (190 x 350 m), corresponding to an 0,5 m^2 per capita. The detailed plan of the WWSTP is presented in Figure 3.4.

Figure 3.3: Location of the wastewater and sludge treatment station.

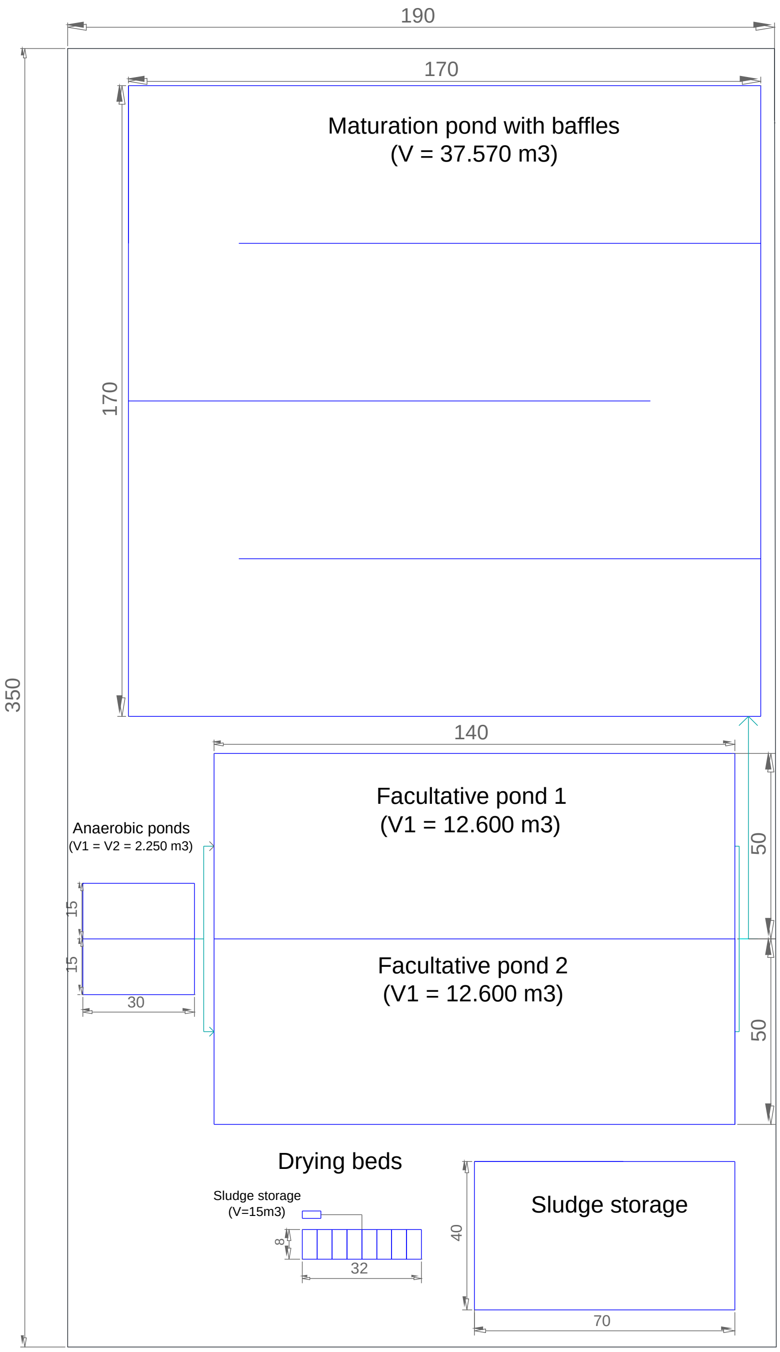

Figure 3.4: Dimensions of the Wastewater and Sludge Treatment Plant (meters).

Conclusions

The management of faecal sludge is based on a set of activities, essential to ensure that the excreta is properly managed during the whole cycle, from the origin in semi-on-site sanitation systems to the final destination. These sanitation systems are the most widely used type of sanitation in developing countries, being essential to have solutions to manage the sludge in a secure way to the environment and without risk to public health. The urban environment presents major challenges for the management of faecal sludge, because they are normally characterized by high population growth, resulting in high population densities with added challenges. In general, cities in developing countries in general, do not have the infrastructures to respond adequately to the urban growth, with few waste management services, weak monitoring and maintenance of existing systems. The approach to the management of faecal sludge must be adapted to the location, planning the system in conjunction with communities and local authorities, with solutions adapted to the climate conditions and possibilities of the region.

There are several technical options to perform the collection, transportation and treatment of faecal sludge, as well as final destination alternatives. Currently most of the solutions to the faecal sludge management consist of the direct implementation of conventional systems of developed countries, where it is very important to consider the differences of faecal sludge and sewage characteristics. The case study of this dissertation was performed on a fragment of the city, concluding that the high dimension of cities is a determining factor to plan faecal sludge management, justifying the decentralization of the treatment system. It is concluded that the future planning of the use of urban spaces is essential, especially in urban areas, to meet the high population densities and prevent future problems, facilitating the management of faecal sludge and its services, resulting in benefits for the population and environment.

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