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Design of a Semi-Centralized Wastewater Treatment System for Developing Cities: The Case of Buea Municipality, Cameroon

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Abstract

The municipality of Buea currently lacks a conventional wastewater treatment system for domestic wastewater. The management of wastewater in the area under study is inadequate, making use of septic tanks, most of which are not constructed following standard norms, and are rarely emptied. The purpose of this work was to evaluate the current system for wastewater treatment and to propose a better conventional system capable of meeting environmental standards. The wastewater treatment system was designed using standard procedures and made use of the trickling filter technology for biological treatment. A gravity sewer was designed for the conveyance of wastewater, followed by primary and secondary settling tanks, and a biological treatment unit which is the trickling filter. The method used for this study involved carrying out a quantitative survey to gather relevant data needed to design the system, followed by the application of standard design procedures. The dimensions of the gravity sewer network made of polyvinyl chloride pipes ranged between diameters of 110 mm and 160 mm. The treatment system includes two primary settling tanks of diameters of 8 m and heights of 2.5 m, two trickling filters of diameter 26.4 m and height of 3.6 m, and two secondary settling tanks with a diameter 8m and height of 4.5 m. The theoretical performance of the system showed a Biochemical Oxygen demand reduction from 222 mg/L to 16.3 mg/L, Total Kjeldahl Nitrogen reduction from 55 mg/L to 22.5 mg/L and total Phosphorus reduction from 15 mg/L to 9.5 mg/L. The pollution reduction exhibited by the system enables the treated wastewater to meet the country's environmental discharge standards. The design proposed with a cost estimate of about 1,528,023 USD (United States Dollar) is relatively low compared to constructing a septic tank for the households in the study area which costs about 4,183,041 USD. The system proposed is less costly at a city scale and more environmentally friendly compared to a standard septic tank. Hence such a system is recommended for developing cities especially Buea.

Keywords: Sewer network; Trickling filter; Wastewater treatment plant; Gravity sewer; Settling tank

Introduction

In recent years, there has been increasing concerns with regards to the management of sewage in many parts of the world and Africa in particular. Water scarcity and water pollution phenomena pose a critical challenge in many developing countries and especially in urban areas where the authorities increasingly face difficulties in managing water supply and the generated wastewater [1].

The Municipality of Buea is located in the south-west region of Cameroon and depends almost totally on groundwater for potable water supply. This limited resource ought to be protected from pollution, to ensure that it meets the needs of the present generation without compromising the ability of future generations to meet their own needs. The predominant sanitation infrastructure used for the treatment of domestic wastewater is the septic tank. However, most of the septic tanks existing in the study area do not have a drain field, are deficient in the way or the other and desludging is rarely done. This confirms the use of septic tanks in Cameroon is not very efficient and desludging is hardly done [2].

It has however been observed that land use activities, including poorly constructed septic tanks, pose a risk to certain source waters in Buea [3]. Given that most of the septic tanks are poorly constructed, deficient and not functioning properly, there is a risk of pollution of groundwater resources in this area and hence a precautionary approach is required [3]. Due to the increasing difficulty faced by households in managing autonomous sanitation infrastructures like septic tanks in Buea, a semi-centralized sanitation system is thought to be more adequate to this area.

Semi-centralized systems have been used for wastewater treatment in certain parts of the Country such as the city of Yaoundé but made use of the activated sludge method. Most of them failed due to the high cost of construction and maintenance. Hence there was a need to find a well suited low-cost technology in terms of construction and maintenance for the treatment of wastewater in the study area. This led us to the choice of the trickling filter technology. The trickling filter technology has been widely used for centralized as well as semi-centralized systems but has never been used in Cameroon; hence we saw the need to apply this technology for the design of a treatment system for the municipality of Buea in Cameroon.

This work proposes a design of an integrated system that collects transports and treats wastewater in order to provide an optimal solution for wastewater management in Buea, Cameroon.

Materials and Methods

Study area

The study area comprises of three neighborhoods in the municipality

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of Buea and includes Clerks quarter, Federal quarter and Old government station. The detail of this is shown below (Figure 1). The study area has a total population of about 8,999 inhabitants according to the last census report and an annual growth rate of 2.8% according to the National Institute of statistics. The population here is highly cosmopolitan, putting the indigenes at a minority.

In effect, it has an equatorial climate with 2 major seasons. Rainy season which runs from March to October and Dry season, from November to May. Temperature ranges between 20 degrees Celsius to 28 degrees Celsius while annual rainfall ranges between 3000 mm to 5000 mm. The soil type consists of basalts and is as a result of the first volcanic activity in the Fako Mountain area, which occurred in the Cretaceous system. These soils have been weathered and partly covered by more recent deposits, thus the soils are black and in these areas are well drained due to the generally hilly nature of the terrain and the fact that they are free-draining.

Sampling method

This study made use of simple random sampling to choose the households. The study area is a government residential area and houses are well structured following a similar pattern. A sample size of 150 households was randomly chosen to fill the questionnaires. A semi-structured interview was carried out in 8 institutions in the study area.

Information was obtained regarding the type of sanitation system in use, the level of satisfaction by households, how often maintenance is done and how the system is managed, the average number of persons per household, Socio-economic status, general perception of the system to be proposed, and the willingness to pay if the newly proposed system is to be put in place.

A visual appraisal of the current sanitation system was also done and the different road networks in the area were analyzed, to choose the best route to lay the sewer for the conveyance of wastewater to the potential location of the treatment plant. A graphical presentation of the results was done using Microsoft Excel and the design of the sewers and treatment plant was done using standard procedures. AutoCAD 2016 student version was used to draw the designed sedimentation tanks, the trickling filter and the general layout of the plant. Quantum (Q) GIS Desktop version 2.14.3 was used to draw the different maps of the study area and for digitization. Open Street Maps (OSM) 2015 was used to capture the image of the area.

Dimensioning of the Sewer

Design parameters for the transport network

The sewer network was designed by first imposing the slope, and then the velocity of flow in the pipe was calculated, to ensure it can permit flow of sewage. Manning's Formula was then used to calculate the diameter of the pipes.

Calculating the population to be served (Pop)

The population of the entire study area is estimated by counting the number of houses and multiplying by the average number of people per house in Cameroon: given at ~5 people per house in urban areas and then using the formula for a 2041 projected population:

$$Pm=Pn(1+r)^n \quad (1)$$

Where:

P_n=Actual Population (House count × number of people per house)

P_m=Population number at the target year (2041 for this design)

r=Present population growth rate

n=design period

This population estimate was done for every section, so as to calculate the diameters of the pipe for the various portions of the wastewater network

Calculating the daily flow rate (Q_{24}, L/s)

The daily flow rate was calculated by:

$$Q_{24}=1.5 \times d \times Pop \quad (2)$$

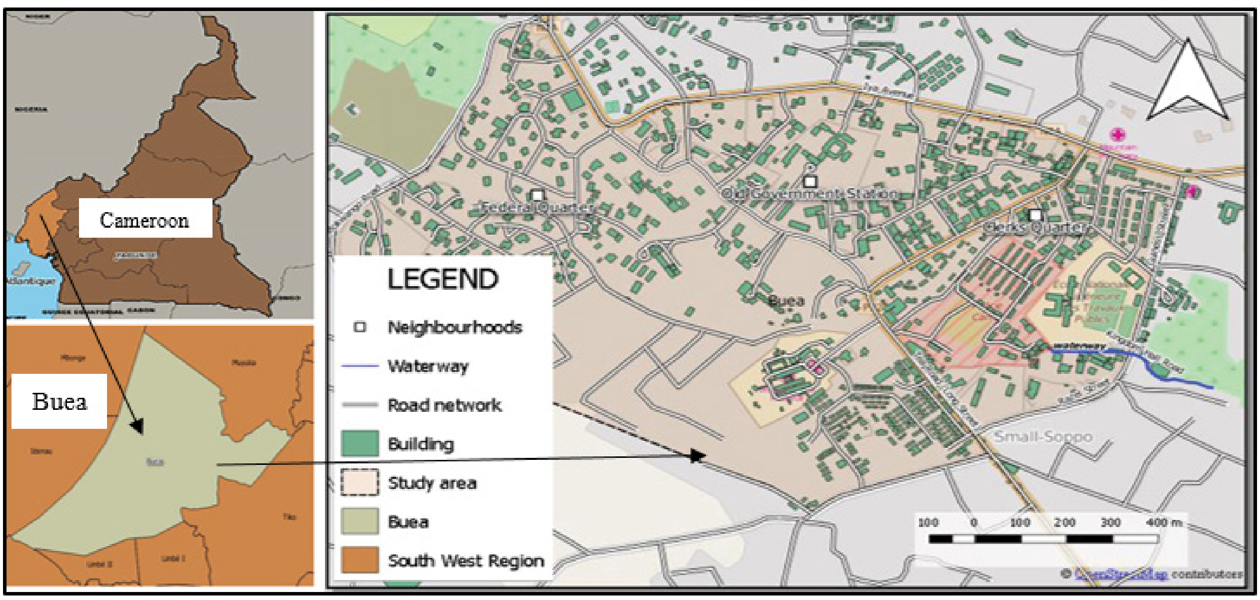

Figure 1: Map showing location of study area.

Where: d=Daily potable water supply (80 L/day/inhabitant for the study area).

Calculating the peak flow rate (Q_{max}, m^3/s):

The peak flow rate was calculated by

$$Q_{max} = 1.5 \times Q_{24} \quad (3)$$

The manning's constant

The proposed pipe material is Polyvinyl Chloride (PVC). PVC is favored because it is light-weight but strong. It is also smoother than other materials and highly resistant to corrosion. Other types of pipes, such as concrete pipes are susceptible to corrosion due to acid and hydrogen sulfide attack.

Manning's constant for PVC pipes is n=0.011 $s/m^{1/3,}$ the chosen value was n=0.012 $s/m^{1/3}$ to account for aging of the pipe.

Calculating the pipe diameter (D_{calc}, m):

The diameters of the pipes were calculated using the Manning's formula thus:

$$D = \left(\frac{Q_{\max} \times 4^{\frac{5}{3}}}{Ks \times \pi \times I^{\frac{1}{2}}} \right)^{\frac{3}{8}}$$

But K=1/n and imposed slope, I= 0.3%

$$D = \left(\frac{\left(4^{1.67} \times Q_{max} \times n\right)}{\left(3.14 \times i^{0.5}\right)} \right)^{0.375} \quad (4)$$

Choosing the commercial pipe diameters (DN, mm)

The calculated pipe diameters were then compared with the available commercial diameters and a choice was made by choosing the next bigger pipe diameter that corresponded to the calculated pipe diameter.

Calculating the speed of flow (V, m/s):

The flow within the sewers must retain a sufficient velocity in order to flush out any solids that deposit during low flow

The speed was calculated as:

$$V = \frac{Q_{max}}{A} \quad (5)$$

Dimensioning of the Treatment Plant

Pollutant load

To obtain the pollutant load of the wastewater, we use the notion of Person Equivalent, which is the standard pollution charge per person in a day. It is a commonly used unit of measurement to quantify pollutants in wastewater. Person Equivalent is a standardized definition of the daily pollution charge emitted on average per capita. The pollutant charge per person equivalent for Buea is indicated below (Table 1).

The average flow rate, Q_{24} was obtained by adding the volume of urban wastewater (total hydraulic charge), with the volume of parasitic water (assumed to be 20% of urban wastewater) generated per day.

The peak flow rate (Q_p) was then calculated as follows

Hydraulic Charge		80 L/day
Organic and Nutrient Charge	Suspended Solids(SS)	32 g/day
	Biochemical Oxygen Demand (BOD)	32 g/day
	Total Kjeldahl Nitrogen(TKN)	8 g/day
	Total Phospurus(TP)	2 g/day

Table 1: Pollutant charge per person equivalent (PE).

$$Q_p = 1.5 Q_{24}$$

Where 1.5 is the peak factor and Q_{24}=daily or average flow rate

Preliminary treatment

Preliminary treatment consists of removing floating materials like wood and rags etc. It is necessary so as to protect pumps and other equipment from mechanical damage and easy wear out. It also helps in the removal of grease and oil and reduces BOD by about 15%. The processes involved are:

1. Screening: to remove floating papers, rags, and clothes
2. Grit chamber: to remove grit and sand
3. Skimming: to remove oil and grease

Screens

The surface area of Screen

$$A = \frac{Q_p}{Vs \times C \times O} \quad (6)$$

C=charge coefficient, *O*= relative free space between bars, V_s= entry speed of wastewater
The width of Screens,

$$W = A/Lo \quad (7)$$

Where L_O = wetted width, A=area

$$Lo = Te / \sin\theta \quad (8)$$

T_e= water draught (20 cm), θ=angle between the oil surface and foot of grit (26.5)

Refuse production from Large screens=Total P.E × (15 L/day/PE)/60 (screen spacing e=60 mm)

Refuse production from Smaller screens=Total P.E × (15 L/day/PE)/10 (screen spacing e=10 mm)

Grit chamber design

Contact time=6 minutes, Surface loading rate=15 m/h

VThe volumerequired for sand removal,

$$V = Qt \quad (9)$$

Area required for oil removal

$$A = Q/v \quad (10)$$

Dimensioning of Primary Settling Tank

Surface loading rate, V_o=1.5-2.5 m^3/m^2h, Hydraulic Retention Time for good settling, HRT=1-5 hours, Depth of tank=2.5 m

The volume of tanks, total volume for 2 tanks

$$V = Q_{24} HRT \quad (11)$$

Hence the volume of one tank, $V_1 = V/2$

From surface loading rate,

$$v_o = Q_{24}, \quad (12)$$

Area of tanks,

$$A = Q_{24} / v_o \quad (13)$$

The diameter of the tank,

$$D = \sqrt{4}\, A/\pi \quad (14)$$

Dimensioning of Trickling Filter

This unit is necessary to remove dissolved organics and nutrients from wastewater mainly by bacterial action. This is an attached growth process.

Filter media=lava rocks

Number of biological reactors=2

Shape of biological reactor=Round

Parameters: Applicable BOD Loads for trickling filters are indicated below (Table 2).

Total Volume of filter

$$V\left(m^3\right) = B_d / B \quad (15)$$

B_d= BOD supply (kg BOD/day) B=applicable BOD load in trickling filter obtained from the table above (kg BOD/m^{3}day).

The volume of one tank, $V_1 = V/2$

Total Area of the filter,

$$A = Q_{max} / V_o \quad (16)$$

Q_{max} =peak or maximum flow rate Vo=acceptable hydraulic loading in trickling filter, obtained from Table 2 above.

The diameter of the tank,

$$D = \sqrt{4}\, A/\pi \quad (17)$$

The height of the filter,

$$H(m) = V(m^3)/A(m^2) \quad (18)$$

Recirculation is usually required for good functioning of the filter; hence we need to calculate the recirculation flow rate, Q_R.

$$Q_R\left(m^3/h\right) = Q_{Opt} - Q_{24} \quad (19)$$

Where

$$Q_{Opt} = AV_o \quad (20)$$

Dimensioning of the secondary settling tank (Clarifier)
Total flow entering clarifier,

$$Q_c = Q_{24} + Q_R \quad (21)$$

	High Load	Medium Load	Low Load
BOD Load(kg BOD/m³day)	0.7-1.0	0.3-0.5	0.1-0.2
Hydraulic load, V_o(m³/m²h)	0.7-1.5	0.4-0.8	<0.2
Oxidation	BOD	BOD-TKN	BOD-TKN

Table 2: Applicable BOD load for trickling filters.

Area required for peak flow conditions:

$$A_p = Q_p / v_p \quad (22)$$

Area required for average flow conditions:

$$A_{24} = Q_{24} / v_{24} \quad (23)$$

For better design, we choose the largest area

The diameter of the tank,

$$D = \sqrt{4}\, A/\pi \quad (24)$$

Results and Discussion

The predominant user interface (toilet)

The predominant user interface in the study area is the water closet or pour flush toilet with about 77.3% of the household using it (Figure 2). The predominant user interface in the study area is compatible with the semi-centralized sanitation system been proposed.

The desludging frequency of septic tanks

It was necessary to verify how often desludging is done for the septic tanks in the study area. This gives an indication of how the system is managed. The results as indicated in shows that 34.7% of the septic tanks have never undergone desludging and 28% undergo desludging after a period greater than five years (Figure 3). This is problematic to the environment and contrary to the 2 to 5 years recommendations [4]. This result also confirms that septic tanks in Cameroon are not very efficient and desludging is hardly done [5].

Socio-economic status of the respondents

This is important to verify if the people in the study area are able to pay for the services, in case a semi-centralized system was to be put in place. We can observe that about 86.7% of the respondents are relatively high-income earners and are believed to be able to pay for such services (Figure 4).

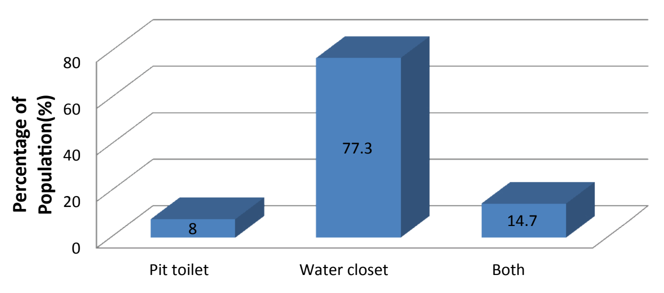

Figure 2: Predominant user interface in area.

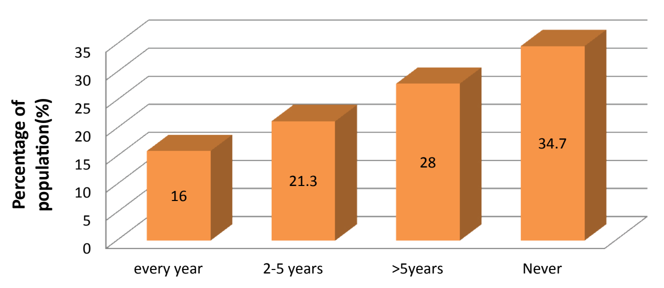

Figure 3: Desludging frequency of septic tanks.

Willingness to pay

Given the fact that ability to pay is not a willingness to pay, it was necessary to see if the respondents are willing to pay [6]. According to study, a household should not pay more than 2% of its earning on sanitation. Hence respondents who choose at least 1% of their monthly earning were considered willing to pay. From the survey results, it can also be seen as indicated in that 82.7% of the population is willing to pay for improved sanitation services in the case where the design proposed is executed (Figure 5a).

It was also necessary to understand the perception of the respondents with regard to the system been proposed and to see if it is accepted by them [7,8]. About 70% of the respondents accepted the semi-centralized sanitation system (Figure 5b).

These results from the survey indicated that majority of the population accept the technology and the system proposed and are also willing to pay in the case where they are to contribute for the construction of such a system. These two aspects are vital for the long-term sustainability of the treatment system [9].

The designed gravity sewer

The pipes designed for the sewer network have commercial diameters ranging from 110 mm to 160 mm and velocity in the pipe ranges from 0.25 to 0.50 m/s as seen in Table 3.

The velocity obtained in the sewers ranges between 0.25-0.50 m/s similar to 0.2-0.4 m/s obtained for the city of Paraty in Rio de Janiero, Brazil [10]. This is, however, less than the most commonly recommended self-cleansing velocity of 0.6 m/s in Brazil and America. Velocities of 0.6 m/s for separate sewers transporting domestic wastewater is hardly achieved especially with partially full pipes and hence there is a need for more studies and recalibration to obtain a commonly achievable self-cleansing velocity especially in less developed Countries.

This table shows the commercial diameter of the pipes used for each section of the sewer network (Table 3). It also shows the velocity of the wastewater at various sections of the sewer. Other parameters such as the population and flow rate as indicated below were used to calculate the diameter and velocity.

The various pipes designated A to N corresponding to different sections of the main gravity sewer shows the potential location of the plant (Figure 6). The main pipe network was chosen following the topography of the area. The study area is has a natural slope which permits free flow right to the treatment plant.

The general layout of the designed wastewater treatment plant

The general layout of the wastewater treatment plant is presented below (Figure 7). It shows how wastewater enters the plant, goes through the screening chamber; grit removal chamber is pumped to the primary settling tank and trickling filter and then is finally clarified in the secondary settling tank. The dimensions of these compartments are also included in the layout.

Designed treatment units for the wastewater treatment plant

The detailed dimension of each unit and compartment of the wastewater treatment plant is indicated below (Table 4). The primary settling tank has a diameter of 8 m and height of 2.5 m, similar to the tank which had a diameter of 7 m and height of 2.5 m for the city of Shiats Allahabad in India [11]. These results are comparable since our system is designed for 24,319 Person equivalents (P.E) while designed for a population of 23,000 Person equivalents (PE). The trickling filter has a diameter of 26.4 m and a height of 3.6 m, which is comparable to that in the treatment plant of Batumi Tskali in Georgia which has a diameter of 28 m and a height of 5 m. Differences in size is due to the relative larger design population of the Batumi Tskali treatment plant [12]. The dimensions of the trickling filter for the plant of Buea also differs from that of the Walvis Bay wastewater treatment plant in Namibia which has a diameter of 45 m and a height of 3 m.

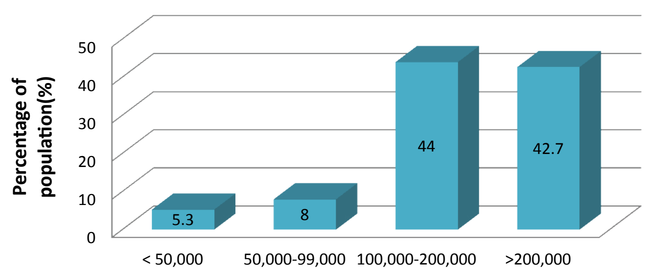

Figure 4: Monthly Income of Respondents in Franc CFA.

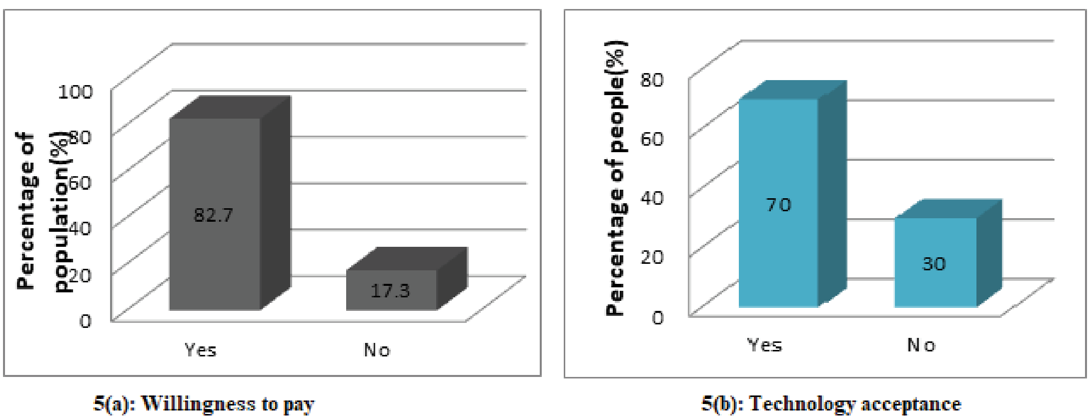

Figure 5: Results from the survey.

Pipe Name	Pop	Q_{24} (× 10^{-3} m^3/s)	Q_p (× 10^{-3} m^3/s)	DN (mm)	Relativity of Flow	Velocity (m/s)	Y/D	Length(m)
A	336	0.438	0.656	110	0.052	0.25	0.32	332.8
B	484	0.63	0.945	110	0.075	0.29	0.38	146.6
C	1034	1.346	2.02	110	0.16	0.28	0.72	192.7
D	282	0.367	0.551	110	0.044	0.25	0.29	95.6
E	322	0.419	0.629	110	0.049	0.25	0.31	152.2
F	349	0.454	0.682	110	0.054	0.25	0.33	62.8
G	402	0.523	0.785	110	0.062	0.26	0.35	237.7
H	3965	5.163	7.744	160	0.2688	0.5	0.72	508.9
I	2294	2.987	4.48	125	0.253	0.5	0.68	490.9
J	723	0.941	1.412	110	0.112	0.31	0.48	143.9
K	846	1.102	1.652	110	0.131	0.33	0.52	184.7
L	4086	5.32	7.98	160	0.277	0.5	0.74	176.8
M	564	0.734	1.102	110	0.088	0.3	0.41	324.5
N	484	0.63	0.945	110	0.075	0.29	0.38	446.5

Table 3: Dimensions of the designed sewer network.

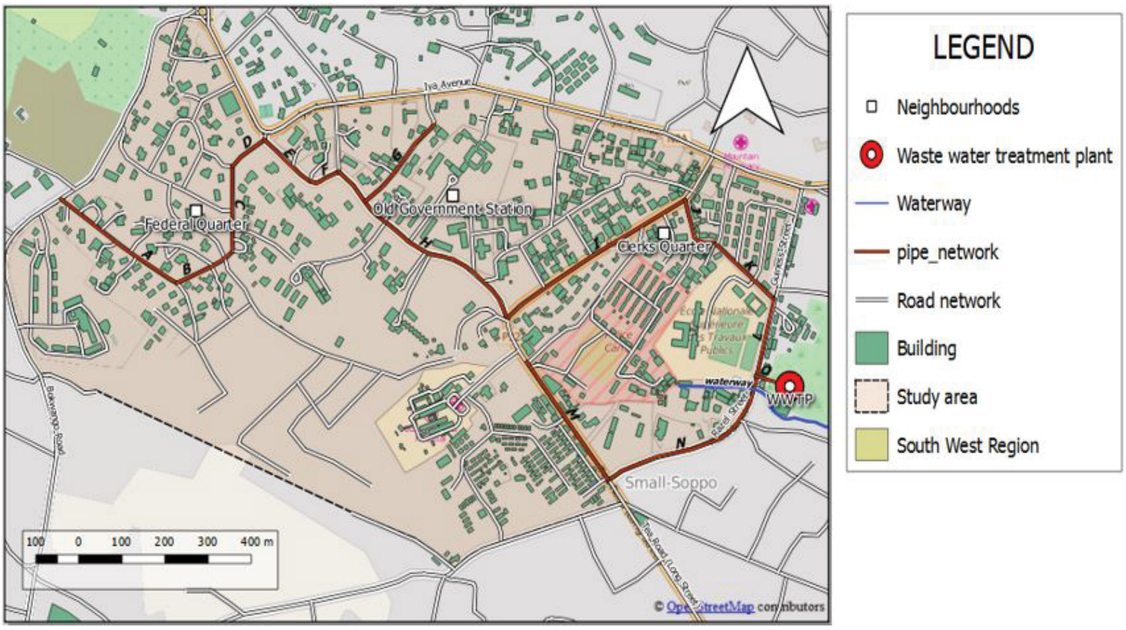

Figure 6: Layout of designed gravity sewer.

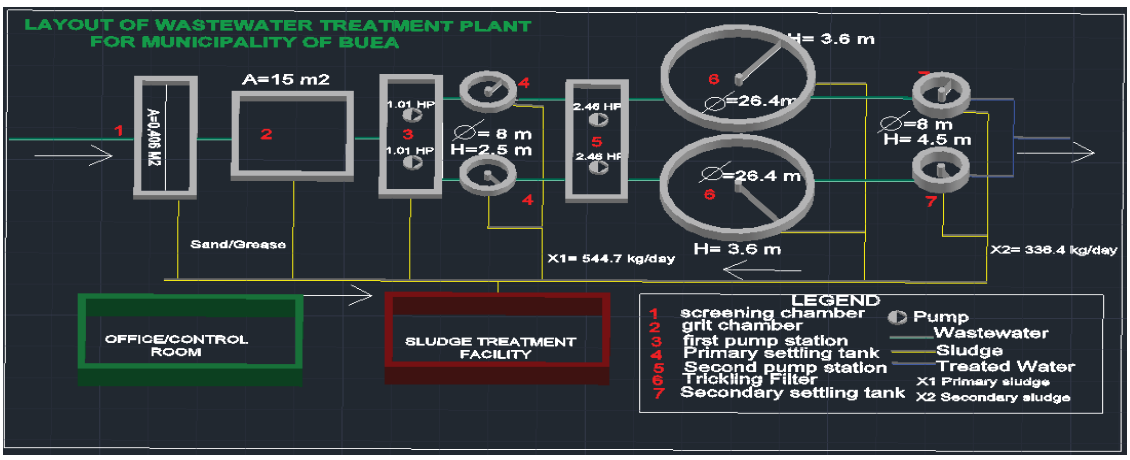

Figure 7 : Layout of the designed wastewater treatment plant with dimension of treatment units.

Compartment	Dimensions
Large screens	Area=0.24 m^2
	Width=53.6 cm
Small screens	Area=0.41 m^2
	Width=90.8 cm
Grit chamber	Volume=22 m^3
	Area=15 m^2
Primary settling tank (no of tank=2 circular)	Volume per tank=110 m^3
	Area per tank=49 m^2
	Diameter per tank=8 m
	Tank height=2.5 m
Biological tank(Trickling filter)	Volume per tank=1945.5 m^3
	Area per tank=548 m^2
	Diameter per tank=26.4 m
	Tank height=3.6 m
Secondary settling tank (no of tanks=2 circular)	Volume per tank=229.5 m^3
	Area per tank=51 m^2
	Diameter per tank=8 m
	Tank height=4.5 m

Table 4: Dimension of the treatment units for the wastewater.

Level of treatment	[BOD_5](mg/l)	[TKN](mg/l)	[TP](mg/l)
Raw wastewater	222	55	15
primary sedimentation	155.4	49.5	13.5
Trickling filter	23.3	32.2	10.8
Secondary sedimentation	16.3	22.5	9.7
National Discharge Standard	<30	<30	<10

Table 5: Pollutant reduction by the treatment plant.

Theoretical performance of the designed wastewater treatment plant

The theoretical performance of the design proposed is as seen below (Table 5). A comparison of the performance is done with the national discharge standard for wastewater, to see if environmental norms are met. From the table we can observe BOD reduction from 222 mg/l to 16.3 mg/L,Total Kjeldahl Nitrogen reduction 55 mg/L to 22.5 mg/L and total phosphorus reduces from 15mg/L to 9.7 mg/L [13]. The pollution reduction is capable of meeting the national discharge standard as seen in Table 5 above.

Cost analysis

The construction cost for the wastewater treatment system proposed is estimated at a value of about 1,528,023 USD. The average cost for construction of a simple septic tank in Cameroon is about 860 USD per household. The study area has about 4864 households hence a total cost of about 4,183,041 USD. If the construction cost for the wastewater treatment system proposed is equally distributed, each household will have an average sum of about 414 USD to pay, while a septic tank will cost a household an average of 860 USD. We can, therefore, see that constructing the wastewater treatment system proposed in this work has a lower cost relative to the septic tank on a global scale.

Conclusion

This study proposes a semi-centralized sanitation system for the municipality of Buea, in view of improving the management of wastewater of domestic origin. The system proposed is less costly (1,528,023 USD) compared to septic tanks (4,183,041 USD) for the same design population in the study area. Furthermore, the system being proposed is able to meet the national discharge standards for wastewater. The system proposed is accepted by 70% of the respondents and is preferred by them relative to the autonomous sanitation system. Most of the respondents are willing and able to pay for the implementation and running of the system proposed. It can thus be concluded that the people in the municipality of Buea continue to use the autonomous sanitation system because they have not been provided with an alternative or better option. Due to the low cost of the system proposed, it could be a better fit for the treatment of wastewater in most African cities.

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