Faecal sludge quantities and qualities (Q&Q) in Lusaka

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Abstract

The need for faecal sludge management in Lusaka is gaining attention from stakeholders throughout the city. To support the design of treatment and management solutions, a study to estimate quantities and qualities (Q&Q) of faecal sludge being produced was conducted by Eawag and UNZA with funding from GIZ. The goal of the study was to estimate expected Q&Q of faecal sludge in Lusaka by categories of demographic, environmental, and technical data that can be spatially referenced (SPA-DET), as described in Strande *et al.* (in preparation). The methodology is based on the hypothesis that categories of SPA-DET data can be used as predictors of Q&Q of faecal sludge based on observed statistical relationships. A total of 421 individual containments were sampled between September and November 2019 (dry season). Locations for sampling were pre-selected, and randomly distributed throughout the city. In situ samples were taken from containments at households and commercial establishments. For each sample, TS, VS, COD, pH, electrical conductivity, volume of containment and volume of sludge were measured. A questionnaire was conducted, and time since last emptied was used to estimate accumulation rates for total faecal sludge accumulation, and of the sludge blanket accumulation. Based on the results, Q&Q accumulating in septic tanks and pit latrines are significantly different, and should be estimated separately. Concentrations of TS and COD were quite variable, and high-end values were on the high end of the spectrum that is commonly observed in other cities in Sub-Saharan Africa. Accumulation rates were also much higher in containments that were emptied recently (<1 year). Significant differences in concentrations of TS, COD, and electrical conductivity were observed between commercial establishments and households. The data collected in this study is useful for the design and planning of management and treatment solutions.

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Introduction

The need for faecal sludge management in Lusaka is gaining attention from stakeholders. Action is needed to counter the spread of water borne diseases. Three faecal sludge treatment plants exist, of which one is currently in operation. The Lusaka Water and Sewerage Company (LWSC) under the Lusaka Sanitation Program (LSP) plans to build several new faecal sludge treatment plants in the coming years, financed by the Word Bank, KfW, African Development Bank, and European Investment Bank. At the same time, Lusaka City Council is responsible for enforcement of sanitation practices. However, management and operation of the existing sanitation facilities and treatment plants brings many challenges. Existing treatment plants are overloaded, out of service, or can only be used intermittently. A preliminary study on faecal sludge quantities and qualities (Q&Q) was done for the newly planned treatment plants, but has been insufficient in providing suitable estimations. Proper estimates for the Q&Qs of faecal sludge that need to be managed in Lusaka are necessary to ensure adequate future design of treatment capacity and management practices.

To support LWSC and LCC in their mission, a Q&Q study was commissioned by GIZ Zambia and conducted by Eawag, in collaboration with the University of Zambia (UNZA). The results of the study are presented in this reported. The aim of the study was to estimate expected Q&Qs of faecal sludge that are accumulating within the defined city boundaries of Lusaka, following the methodology developed by Linda Strande (Strande *et al.* in preparation). The methodology is based on the hypothesis that types of demographic, environmental, and technical data that can be spatially referenced (SPA-DET) can be used as predictors of Q&Q of faecal sludge. The Sandec department at Eawag has conducted multiple Q&Q studies over the past five years to refine the method (Strande *et al.* 2018; Englund *et al.* 2020; Prasad *et al.* in preparation). The Q&Q method is an approach to collect and analyze data in a systematic way, which is adaptable to the local situation and available resources. The structure of the methodology is shown in Figure 1.

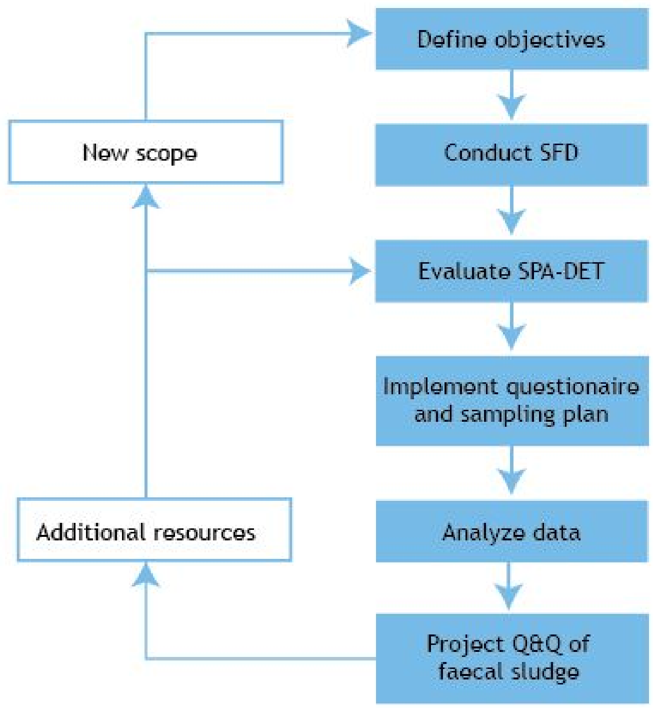

Figure 1: Flow diagram of methodology to estimate Q&Q of faecal sludge (Strande *et al*, in preparation).

Methods

Sampling plan

The sampling plan was designed as follows (text adapted from Strande *et al.* (in preparation)):

For household sampling points:

1. ArcMap software (version 10.6) was used to develop the sampling plan. The official Lusaka city boundaries defined the boundaries of the study, in addition to any areas served by the LWSC outside of these boundaries. Areas where service is provided through the sewer network and the airport were excluded.
2. A layer was added with information on geological formations, and the area was separated by the three different rock formations that are present in Lusaka (Limestone, Dolomite and Schists/Quartzites). It is known that risk of disease from groundwater varies by these locations (Museteka *et al.* 2019), so sample locations were assigned from all three.
3. The area was divided in grid cells of approximately 1km x 1km. Sampling locations were randomly selected by assigning one point to each cell with ArcMap. If a randomly generated point was not on a building, the nearest building was selected. Cells with no, or only a few, households were excluded, in addition to the industrial area, and the area served by the sewer.
4. High density areas were identified based on expert knowledge and visual inspection. They are highlighted in green on the map (Figure 2). In these areas, two sampling locations were identified per cell.
5. During implementation, the field team always went to one of the randomly selected points. If for some reason it was inaccessible this was documented, and then the sample was always taken at the next location *to the right* if facing the building. In this way, the randomness of the sampling was maintained. During sampling, the sampling locations were marked in Google Maps.

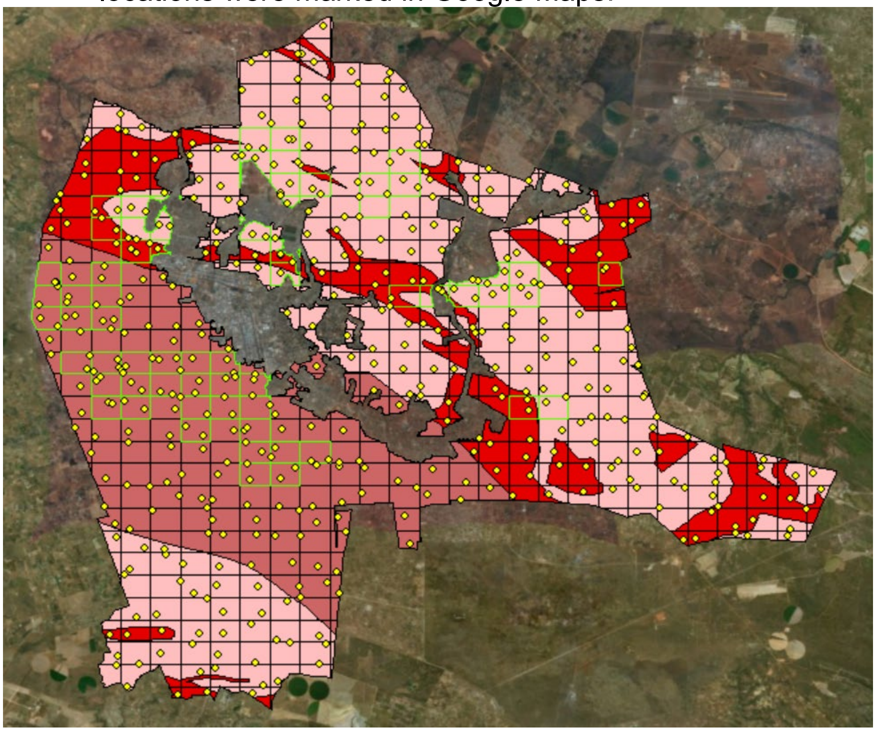

Figure 2: The map of the sampling plan with Lusaka divided in grid cells of approximately 1km^2. Green cells are the identified dense areas where 2 samples per quadrant were taken. Pink is Limestone, red is Schists/Quartzites, and dark red are Dolomite areas. Yellow dots are the randomly selected points.

For commercial sampling points:

1. Samples for commercial areas were separated into four categories: public toilets, office buildings, schools and malls. These were selected because they were determined to be the most relevant for Lusaka based on local expert knowledge.
2. For each of these categories, the goal was to obtain 15 samples spread evenly throughout the boundaries.
3. Non-household sampling points were selected based on local expert knowledge. Malls and schools could be identified on Google maps, public toilets and office buildings were identified by the sampling teams and local knowledge (e.g. sampling team drivers, city council members, community leaders).
4. The spread of the commercial sampled points was monitored during the sampling campaign.

Sampling

Upon arrival to the randomly selected sampling site, the sampling team first asked for permission from the owner/tenant of the containment to take a sample, and if granted, the owner/tenant signed a consent form.

While a sample was being taken from the containment, another member of the sampling team administered a questionnaire to the owner/tenant. For household sites, if the owner/tenant was not available, the person in charge of household maintenance was asked. For non-household sites, the person in charge of operating/maintaining the system was targeted. Answers were recorded with the Kobo Toolbox mobile phone app. The questionnaire questions are provided in Annex 1.

Pit latrines

Samples were taken in situ from onsite containments. Due to the wide range of sludge characteristics in Lusaka, different sampling devices were needed to sample from pit latrines and septic tanks. Samples were taken up to a maximum depth of 3m. A metal, conical pit sampler was used for sampling from pit latrines, which was a modified version of the sampler in (Tembo 2019) (Figure 3). The sampling device was used to take a sample at the bottom of the pit (or as deep as the pit sampler reached, 3m) the middle of the pit and from the top of the pit. The three sub-samples were mixed thoroughly in a bucket with a ladle, and a composite sample was made for analysis.

Figure 3: Cone-shaped pit latrine sampling device.

Septic tanks

Samples were taken in situ from septic tanks with a core sampler, the design was based on a core sampler used by CDD Society in Sircilla, India (Prasad *et al.* in preparation). The core sampler consisted of a 3m long transparent PVC pipe (Ø5cm), and a stainless steel plunger (Figure 4). Both the pipe and the plunger could be taken apart into three 1m pieces for ease of transportation. During sampling, the plunger was inserted into the containment until it reached the bottom. Then, the pipe was inserted over the metal rod, and the plunger pulled to seal off the bottom. A stopper on top closed the faecal sludge sample core inside. The whole core sample was then lifted out of the septic tank, and held upright for approximately 1 min to let the sludge blanket settle. The core sampler was graduated to be able to measure the depth of the sludge. Both total depth of the sludge and depth of the settled sludge blanket layer were recorded. Afterwards, the sludge core sample was emptied into a bucket, and stirred well with a ladle to ensure a homogenous sample.

Figure 4: The core sampler with a settled sample from a septic tank.

Quantities

Volumes of on-site sanitation containments and the in situ volume of faecal sludge were measured with a Volaser. The Volaser is a measuring device that can measure faecal sludge in situ volumes with a distance-laser module and a probe. The laser unit is mounted on a tripod-stand, and is operated via a smart phone app. The phone is mounted on top of the tripod, the tripod is then set up over a vertical access port to the containment, and is lowered so that the laser-unit is fully inside the containment. Then, the measurement is started in the app, and the top part is rotated while the laser measures the distance to the walls, and the angle of rotation, and then calculates the area of the containment. Depth of the containment was measured physically with an avalanche probe (BCA Stealth carbon, 300cm) (Figure 5). The sampling team had a standardized form on which the area and depth of the containment, depth of the sludge layers, containment type, and any challenges/irregularities were recorded (Annex 2).

Figure 5: The Volaser in its storage position (left). Volaser measurements being taken in a septic tank (middle). The avalanche probe used to measure depth (right).

Analytical methods

Laboratory analysis was done at the Environmental Engineering laboratory at UNZA. pH, EC, TS, VS, and COD were measured following standard methods (APHA 2017). COD standards were not used because due to the short time period of project implementation they could not be obtained. In the coming months, once standards can be delivered, UNZA will run trials to evaluate the accuracy of the method. Stakeholders will be informed once these are completed. Density was calculated for 273 samples by weighing 25mL of sludge.

For pit latrines the total faecal sludge accumulation rate was calculated. For septic tanks, the total faecal sludge accumulation rate was calculated using the total volume of liquid/sludge in the tank, and also the sludge blanket accumulation rate was calculated.

Faecal sludge accumulation rate (L/cap·year) was calculated as

$$\frac{Volume\ of\ faecal\ sludge\ inside\ conatinment\ (L)}{(Number\ of\ users\ (cap) \times Time\ since\ last\ emptying(year))}$$

The following assumptions were made to calculate faecal sludge accumulation rate:

1. For septic tanks, if the respondent indicated that the septic tank had a baffle, then it was assumed that the Volaser only measured the first chamber of the tank. To estimate the total area, the surface area of the tank was measured with a measuring tape. The area measured with the Volaser was then multiplied by the ratio between the area measured with the Volaser divided by the outer dimensions of the tank.
2. If the respondent indicated that the containment was emptied, but not completely, the volume of faecal sludge inside the containment was divided in half to account for the faecal sludge left in the tank. This number was based on expert knowledge and data from Tembo (2019). Pit latrines are commonly emptied with 12 barrels, 24 barrels or 36 barrels. Depending on the containment volume, in Tembo (2019) this was on average between approximately 20-60% of the containment volume, with the majority of pits being emptied approximately 45% of their total volume. Therefore, 50% was selected as a reasonable average for both pit latrines and septic tanks.

Sludge blanket accumulation rate (L/cap·year) was calculated as

$$\frac{(Height\ of\ sludge\ blanket\ layer\ (m) \times Area\ of\ containment\ (m^2) \times 1000)}{(Number\ of\ users\ (cap) \times Time\ since\ last\ emptying\ (year))}$$

Data cleaning was done in Microsoft Excel, and data analysis was done with R software (version 3.4.1 “Single candle”). Faecal sludge accumulation rate and sludge blanket accumulation rate measurements were inspected and measurements with clear errors were removed before analysis.

Quality Assurance/Quality Control (QA/QC)

Sampling

To evaluate the precision of the sampling method, a sampling duplicate was taken every 20th containment, and a sampling triplicate was taken every 100th containment. It was ensured that these were taken from both pit latrines and septic tanks. In the data analysis, these were analyzed per containment with the mean and standard deviation, and then for each parameter the average relative standard deviation was calculated.

Additionally, results of in situ sampling were compared to sampling that was done while emptying for 13 samples (8 pit latrines and 5 septic tanks). For pit latrines, which are emptied manually with barrels, 1L of sample was taken from the first barrel, 1L from two of the middle barrels, and 1L from the last barrel during normal emptying operation. These were mixed well in in a bucket and a composite sample was taken for analysis in the laboratory. Septic tanks were emptied with a vacuum truck, and then one 1L samples was taken at the beginning of discharge at the treatment plant, two in the middle, and one at the end. These were mixed well in a bucket and a composite sample was taken for analysis in the laboratory. In the data analysis, these were analyzed per containment with mean and standard deviation, and then for each parameter the average relative standard deviation was calculated.

Laboratory

For pH, standards (6.8 and 10) were measured every day and the probe was calibrated when necessary. The EC probe was calibrated and maintained regularly by a laboratory technician. For TS and VS triplicates were done every five samples. The balance was checked daily with a standardized weight. For COD, triplicates were done every ten samples, and blanks were measured at the start of every batch. For triplicates, the average of the three measurements was used. Extreme values were analyzed carefully and if, based on expert knowledge, the measurement was rejected, an average of the duplicate was taken instead.

Results

QA/QC

The laboratory measurements had relative standard deviations of on average 7% for TS, 5% for VS, and 10% for COD.

Precision of the sampling method within duplicate/triplicate in situ measurements (multiple samples taken from the same containment) had a relative standard deviation of 25.4% for TS, 12.3% for VS, 32.3% for COD, 7.0% for EC and 1.1% for pH. These results reflect the inherent variability with in situ sampling, as rigorous QA/QC measures were followed during this study.

Sampling was done in situ as sampling during emptying is much more expensive and time-consuming, and relies on households calling for emptying services. Based on the results from the QA/QC, this was deemed acceptable. In situ sampling was evaluated by comparing the in situ and ex situ value for each parameter. These are presented in Annex 4. For TS, the relative standard deviation is 40%, and the majority of the measurements were within 30% of each other. For VS, the relative standard deviation is 14%. For COD, the relative standard deviation is 24%. For pH, the relative standard deviation is 2%. For EC, the relative standard deviation is 11%. Clearly there are differences between the methods. This could be due to differences between what accumulates in situ versus what is sampled during emptying/arrival to treatment plant, and also importantly due to the inherent heterogeneity of faecal sludge. Upon commissioning of the new treatment plants, this can be further evaluated.

Sampling

A total of 421 individual containments were sampled, consisting of 39 unlined pit latrines, 68 partially lined pit latrines, 100 fully lined pit latrines, 197 septic tanks, 3 cesspits, and 14 that were classified as unknown (Figure 6).

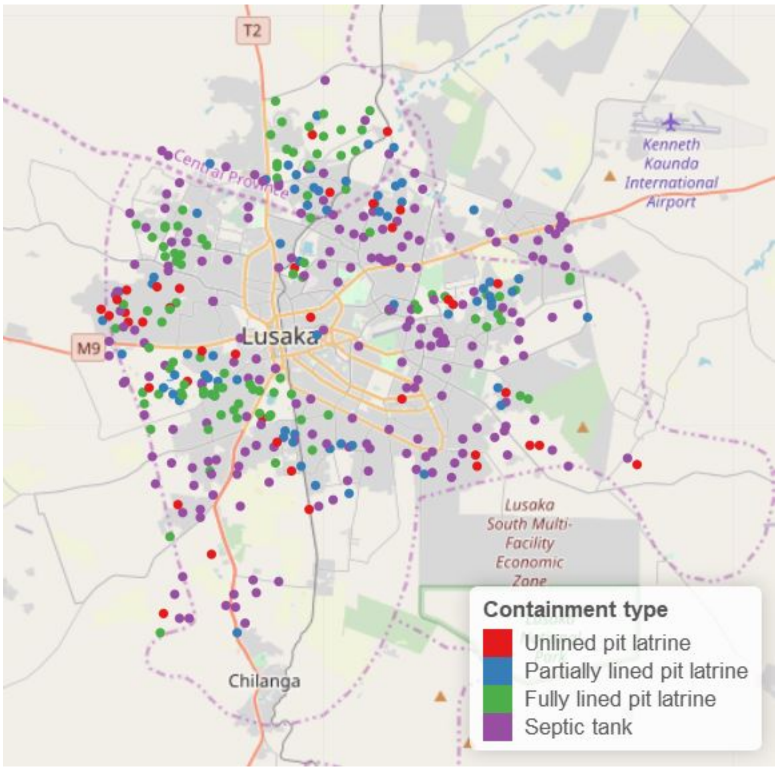

Figure 6: Spread of samples taken by different containment types (cesspits and unknowns not shown).

A relationship was observed between containment type and income level (Figure 7). Households with a higher income were more likely to have a septic tank, and in lower income households were more likely to have unlined pit latrines. Income is difficult to measure by questionnaire, as people might not always feel comfortable to answer honestly. In the questionnaire we tried to reduce the bias in this parameter by providing category answers to choose from (based on expert consultation during the kick-off workshop), but uncertainty of the accuracy of results remains. In the future, one might want to think about other ways to measure economic status, for example with an asset index, although the data analysis for this is more complicated (Filmer & Pritchett 2001).

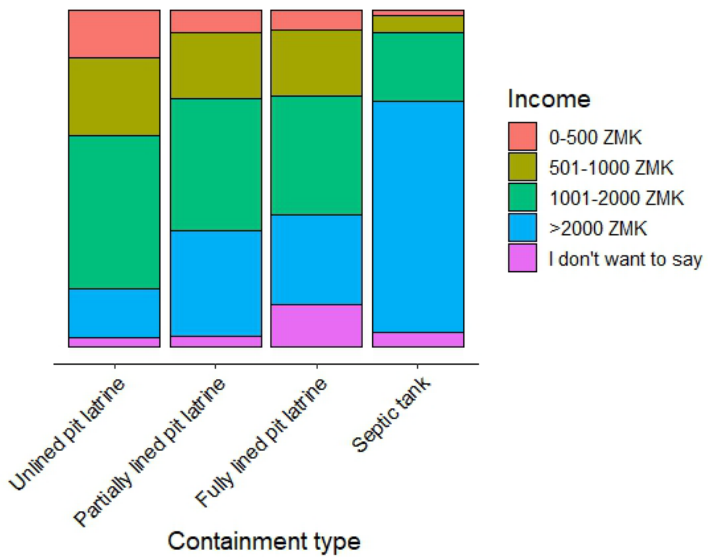

Figure 7: Containment type separated by income level for households.

There is also a relation between type of containment and whether there was a water connection on the premises (Figure 8), where premises with a septic tank more often had a water connection.

There was no relation between categories of geology (Dolomite, Limestone and Schists/Quartzites) and type of containment.

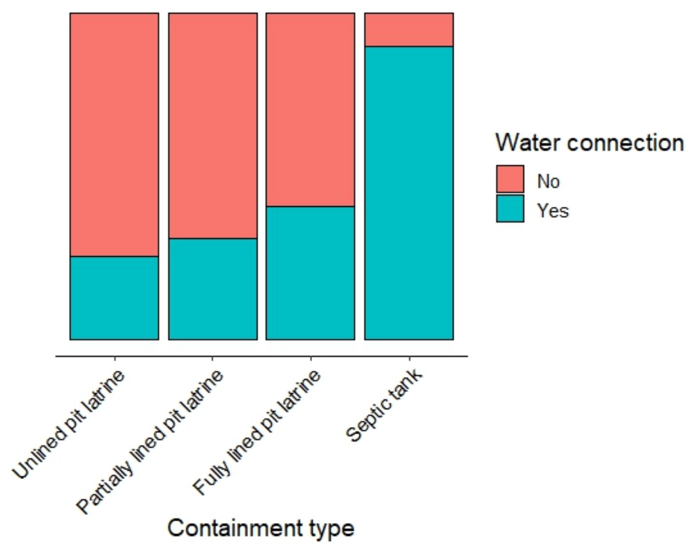

Figure 8: Bar plot containment type by whether there is a water connection on the premises.

Qualities

Out of 421 samples, 4 were removed from the analysis for faecal sludge accumulation, due to error. Cesspits (n=3) were taken out from the 'Containment type' category due to the lack of adequate samples.

Density was measured for 273 of the samples, and the mean density was 1.1 g/mL.

A statistically relevant relationship was not observed between the number of users and the measured Q&Q of sludge in Lusaka. This is in contrast to Kampala, Uganda, where number of users was an important predictor to model TS concentrations in pit latrines (Englund *et al.* 2020). Containment age did also did not have a statistically significant relationship with Q&Q of sludge in Lusaka.

Total solids (TS)

Presented in Table 1 are descriptive statistics for the results of TS. Throughout this report, other than in this table, the values for TS are reported as percent of dry TS by weight (% w/w). For the samples were density was measured, it was used to convert the TS by weight into a concentration (g/L). The median in Lusaka corresponds to what other studies report in the higher TS range, including 52.5-66.4 g/L in Accra, and 72 g/L for septage in Manilla (Heinss *et al.* 1999; Appiah-Effah *et al.* 2014). The mean in Lusaka is higher than these values, indicating higher outliers in the high-end range. Presented in Figure 9 are TS in a boxplot, by households or commercial containments. The different categories of commercial containments (malls, schools, public toilets, office buildings) where grouped together because based on analysis of the individual categories, there were no significant differences between them. As illustrated in Figure 9, there is a significant difference between TS of household and commercial containments. Commercial containments had a lower TS than households, which was also observed in Kampala (Strande *et al.* 2018). This could be useful for estimating loadings for design of treatment and management solutions. The mean and the median differ, which means that the data does not follow a normal distribution, and should be taken into account when conducting further analysis.

Table 1: Descriptive statistics for TS by concentration and percent by weight for total number of analyzed samples, and broken down by origin (commercial vs. households).

	Total (g/L)	Total (%)	Commercial (%)	Households (%)
n (number of samples)	273	396	53	325
Mean	101.3	9.7	6.0	10.5
Standard deviation	109.5	8.8	8.9	8.7
10^{th} quartile	3.6	0.4	0.2	0.6
Median	59.3	8.1	1.7	9.7
90^{th} quartile	242.4	20.9	19.6	21.2

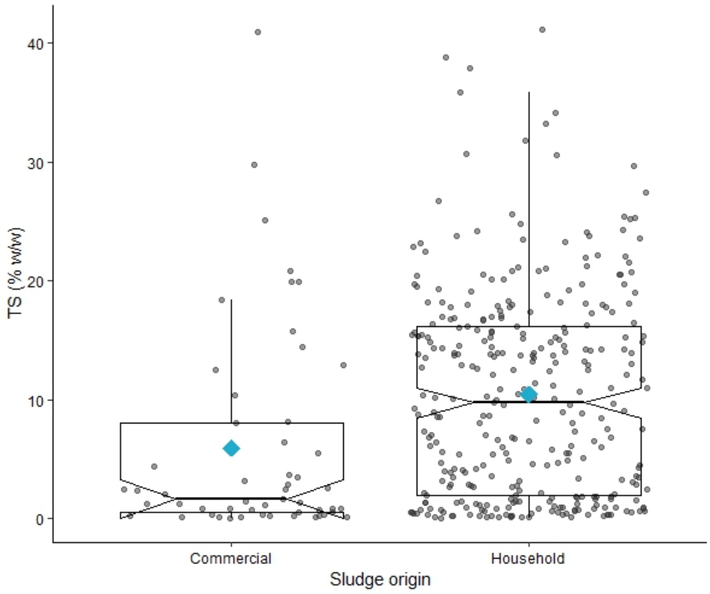

Figure 9: Boxplot TS by sludge origin. The blue diamond represents the grouped mean.

By splitting the data by category in containment type, a significant difference in TS was seen between pit latrines and septic tanks, while between the types of pit latrines (i.e. unlined, partially lined, fully lined) there was no significant difference in median values (Figure 10). Unlined, partially lined, and fully lined pit latrines had medians of 16.5, 14.5, and 13.9% w/w respectively, while septic tanks have a median of 2.1% w/w. The majority of the pit latrines in Lusaka fall within the range of 3-20% TS for pit latrine sludge reported in literature (Semiyaga *et al.* 2015), although there are pit latrines with a much higher TS in Lusaka. The median for septic tanks in Lusaka is within the <3% TS range that is reported in literature for septic tanks (Semiyaga *et al.* 2015), although there are a number of septic tanks with a TS much more than that (Figure 10). It is possible that these septic tanks are not operated or performing as designed.

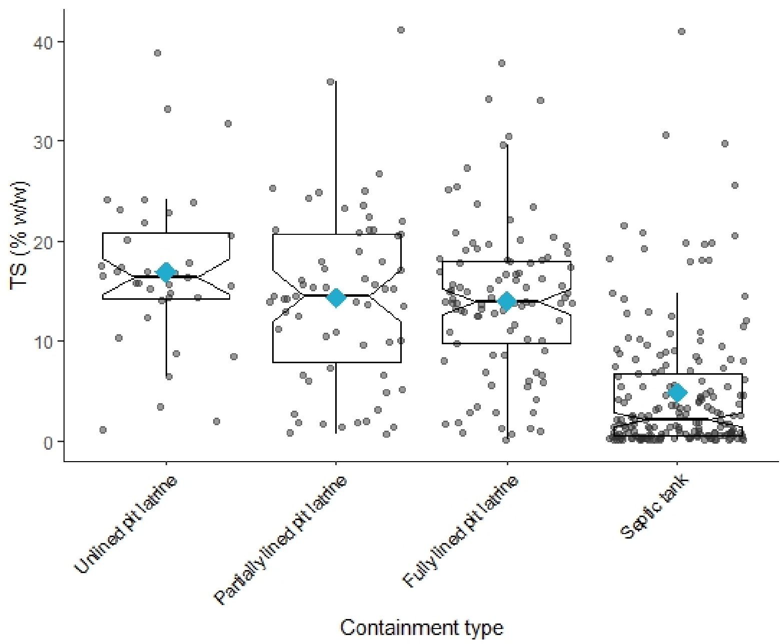

Figure 10: Boxplot TS by containment type. The blue diamond represents the grouped mean.

A significant difference was also observed in TS by the type of toilet flush (Figure 11). Wet toilets (cistern flush and pour-flush) have a significantly lower TS than dry toilets, as expected, due to dilution with flush water. Medians are 14.9, 4.4 and 2.1% w/w for dry toilets, pour-flush and cistern flush toilets respectively, means are 14.6, 7.6, 4.8% w/w respectively. Unsurprisingly, there is also clearly a relation visible between containment type and type of flush, where pour-flush and cistern flush systems in Lusaka are more likely to be connected to a septic tank.

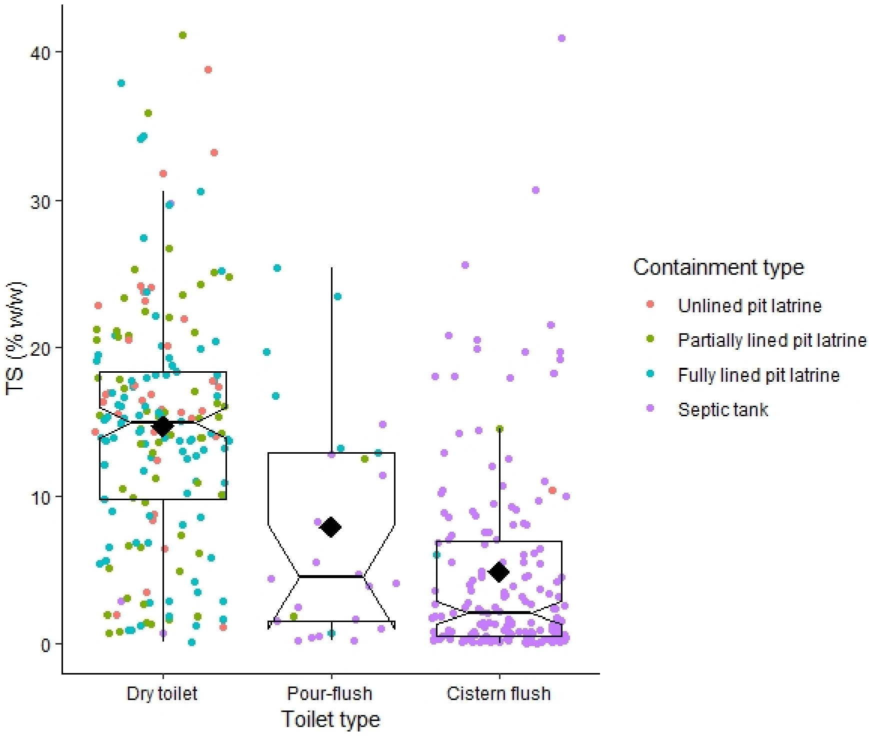

Figure 11: Boxplot TS by toilet type. The black diamond represents the grouped mean.

TS is also significantly if a water connection was reported on the premises (Figure 12). The median values were 14.0% for no water connection and 4.4% for containments with a water connection, and the means were 12.6% and 8.1% respectively. The relationship between water connection and containment type mentioned in Figure 8 is also clearly visible in this figure, where people with a septic tank more often have a water connection, and have sludge with a lower TS.

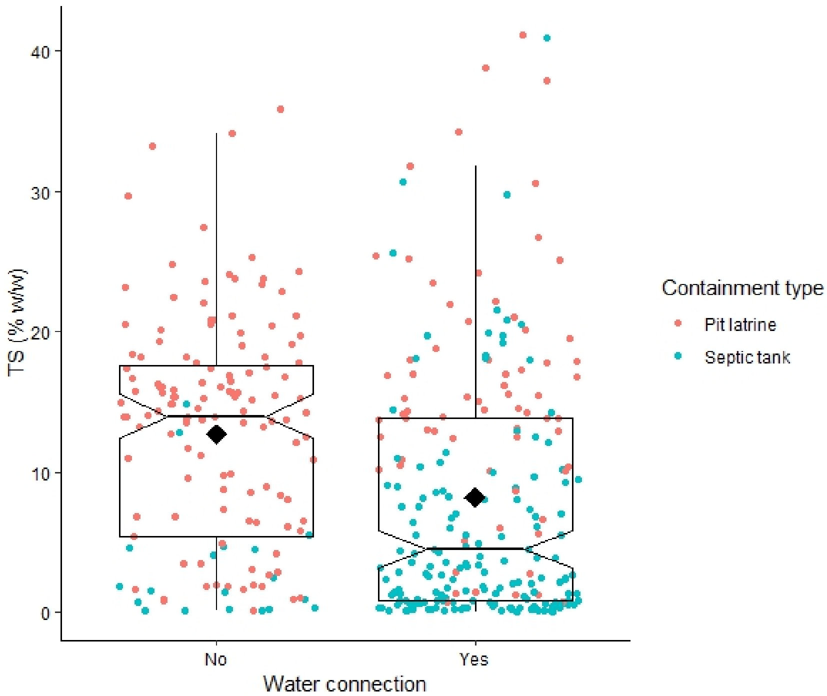

Figure 12: Boxplot TS by whether there is a water connection on the premises (e.g. piped water, a standpipe, delivered by a tanker). The black diamond represents the grouped mean.

When separating TS by income category, TS in containments from households in the highest income category (>2000 ZMK per month) is lower than the other income categories (Figure 13), also related to higher income households more often having septic tanks (Figure 7), which also have a lower TS (Figure 10). However, between the other income categories there is not a visibly significant difference. For the data in Lusaka it therefore makes sense to only make a distinction between high income (>2000 ZMK per month) and lower income (<2000 ZMK per month) households.

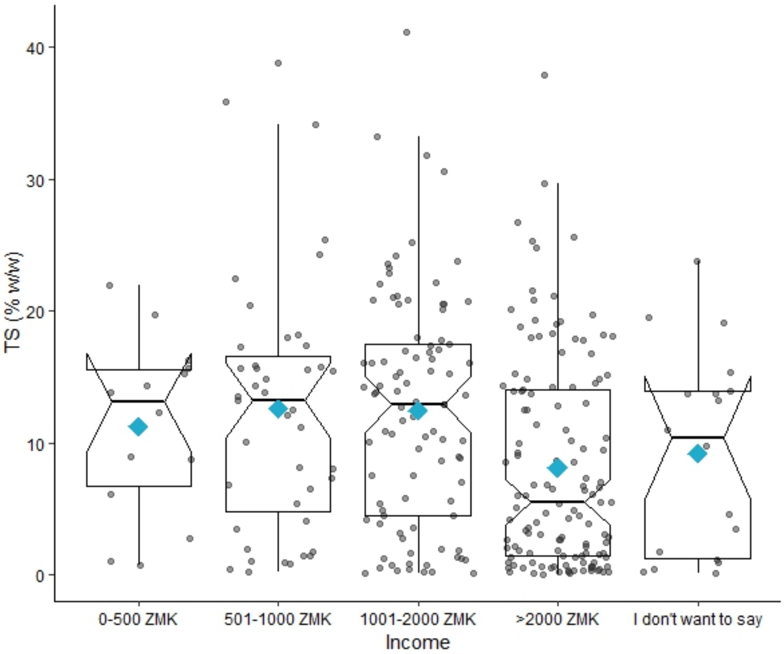

Figure 13: Boxplot TS by household income category. The blue diamond represents the grouped mean.

As recommended by local experts, the questionnaire included a question on whether or not users noticed that the level of sludge changes in the containment during the rainy season. This could be an indication of an unlined or partially lined containment, a leaking tank, high ground water, or other types of inflow or infiltration from the containment. When compared to TS, a significant difference was observed for containments where it was reported that the sludge level is changing (median=13.7%, mean=11.9%) as compared to the containments where there is no change during the rainy season (median=6.5%, mean=9.5%) (Figure 14). TS was measured to be higher in containments where the sludge level is changing seasonally, which makes sense, as this study was conducted during dry season, when water would have leached out of containments that are open at the bottom or leaking.

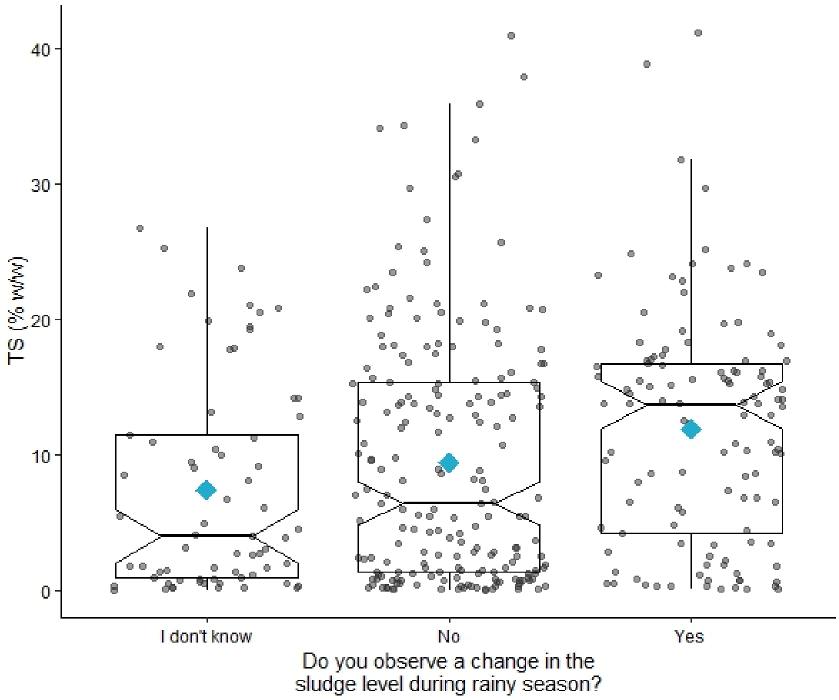

Figure 14: Boxplot TS by whether a difference in sludge level is observed during raining season. The blue diamond represents the grouped mean.

There is also a visible difference between if only black water was entering the containment (Yes), or also additional sources of wastewater (No) (Figure 15). The same trend was also observed in Kampala (Strande *et al.* 2018). It can also be seen that there are more pit latrines that have only black water entering, while more septic tanks have multiple sources of wastewater entering.

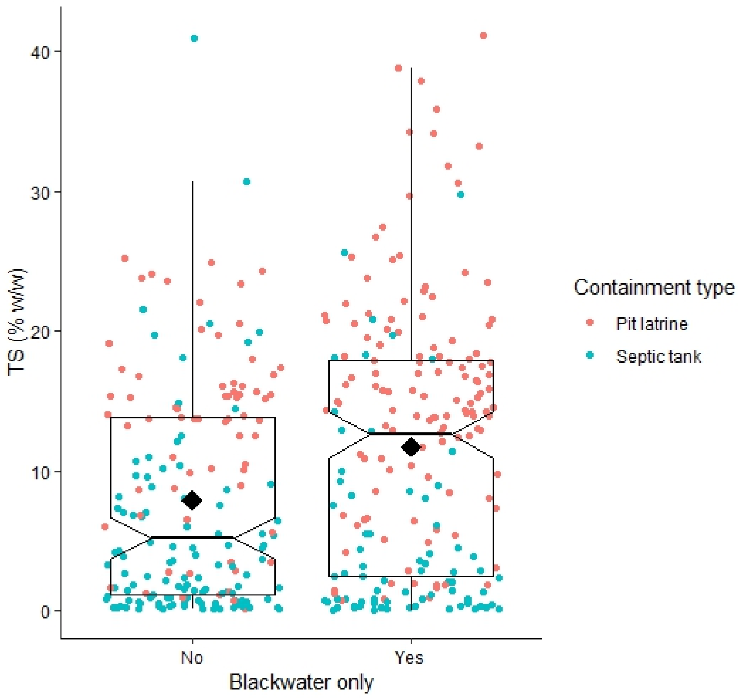

Figure 15: Boxplot TS by whether there was only black water entering the containment, or also additional sources of wastewater (i.e. laundry, kitchen, bathing).

To further investigate the relationships above, a linear model including *sludge origin*, *containment type* with categories pit and septic tank, and *water connection* was calibrated (Table 2). This model indicated that *containment type* has the biggest predictive value for TS. Septic tanks generally have on average TS of 10.4% w/w lower than pit latrines, with high certainty (p-value is significantly low). Sludge origin was not a strong predictor of TS in the model. This may appear unexpected based on Figure 9. Although there is a significant difference between pit latrines and septic tanks, when split by sludge origin (Figure 16), there is no difference between pit latrines or septic tanks in households and commercial establishments left.

Table 2: Linear model outputs for TS.

	Estimate	Standard error	P-value
(Intercept)	14.1	1.3	$<2^{-16}$
Water connection – *Yes*	1.3	1.0	0.18
Containment type – *Septic tank*	-10.4	1.0	$<2^{-16}$
Sludge origin – *Household*	-0.02	1.2	0.98

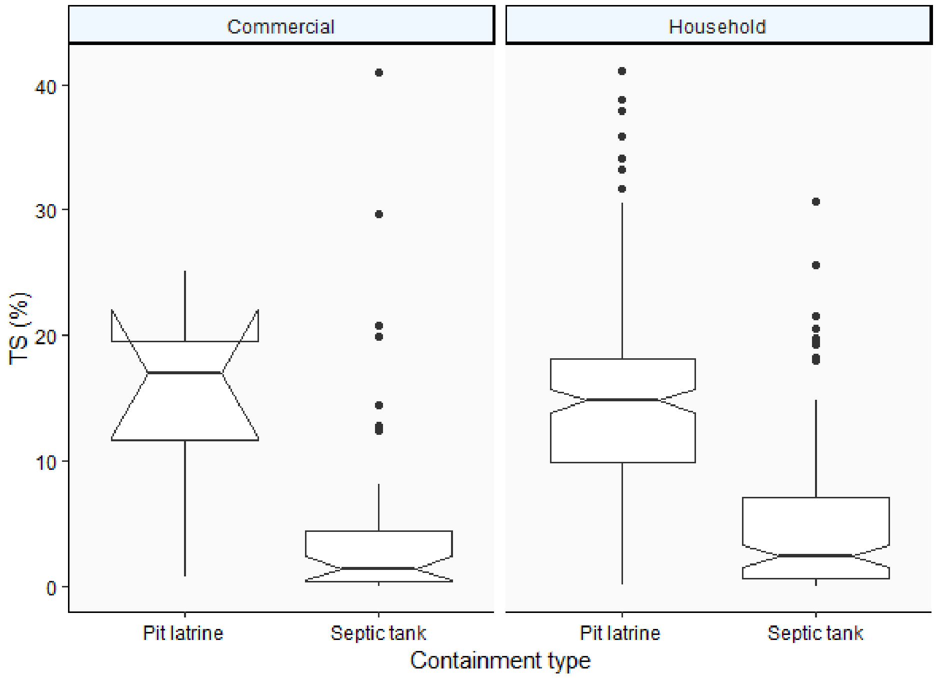

Figure 16: Boxplot TS by containment type, separated by household and commercial sources.

Volatile solids (VS)

For VS, differences based on categories of collected SPA-DET data included containment type, and water connection. A significant difference can be observed between VS and containment type when grouped by pit latrine and septic tank (Figure 17), but it is not very large. For water connection, there visually seems to be a difference, but not large enough to be interesting for application in treatment design (Annex 3). Faecal sludge in Lusaka has a wide range of stabilization. The descriptive statistics are presented in Table 3. The means and medians fit within the range reported for other countries, with a slightly higher standard deviation for septic tanks (Gold *et al.* 2018). The values for VS show a large variability, ranging from 3.4-97.4%. The samples with a very low fraction of VS could be due to a large amount of soil, or a high degree of stabilization. Samples with a very high fraction of VS are all from septic tanks. A possible explanation could be that septic tanks in Lusaka are less stabilized than pit latrines, but there is not enough knowledge to know for sure. The highest of VS values in Lusaka resemble the VS values for fresh faeces reported in Rose *et al.* (2015).

Table 3: Descriptive statistics for VS; total and broken down by containment type (pit latrines vs. septic tanks). NAs were left out for the category breakdown. Units are %TS.

	Total	Pit latrines	Septic tanks
n (number of samples)	385	192	177
Mean	54.8	56.0	53.4
Standard deviation	18.3	16.6	20.2
10^{th} quartile	32.8	35.0	27.7
Median	53.9	58.4	51.5
90^{th} quartile	78.5	76.2	83.3

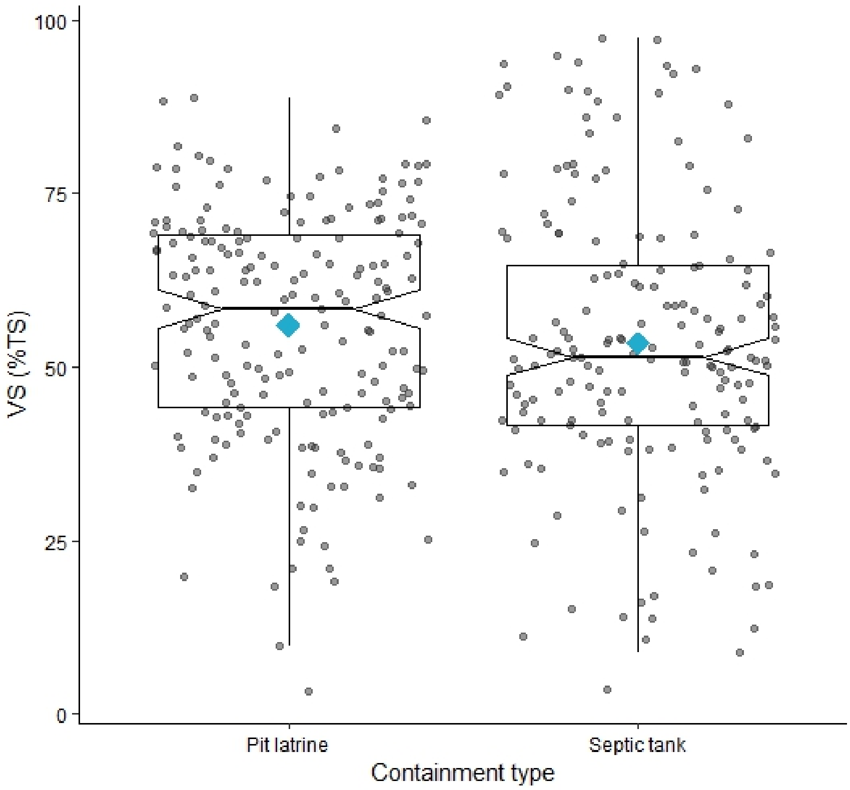

Figure 17: Boxplot VS by containment type. The blue diamonds represents the mean.

Chemical oxygen demand (COD)

The descriptive data presented in Table 4 show a large standard deviation for COD, as has been reported in other studies for faecal sludge (Gudda *et al.* 2017; Gold *et al.* 2018). The higher end values for COD in Lusaka are higher than what is commonly reported in other studies for septic tanks. A mean COD of 16.3 g/L was reported for septic tanks in Kampala (Gold *et al.* 2018) and 7.8 g/L in Accra (Heinss *et al.* 1999). Nevertheless, the higher end values do fall within reported ranges for high strength faecal sludge (Henze *et al.* 2008; Strande *et al.* 2014; Getahun *et al.* 2020). These results for COD, together with the high TS of some tanks, potentially indicate that septic tanks are not being maintained as designed or do not perform as designed.

Studies report similar ranges of COD for pit latrines in other countries in sub-Saharan Africa. In Nakuru, Kenya COD in pit latrines ranged between 72 and 176 g/L with a mean of 112.8 g/L (Gudda *et al.* 2017). In Kampala, Uganda, the mean COD in one study in lined pit latrines was 65.7 g/L and in unlined pit latrines was 132.3 g/L (Semiyaga *et al.* 2017). Another study in Kampala reports 21.6 g/L and 117.6 g/L for lined and unlined pit latrines respectively (Gold *et al.* 2018).

Table 4: Descriptive statistics for COD for all containments aggregated (total), and separated by pit latrines and septic tanks. NAs were left out for the category breakdown. Units are in g/L.

	Total	Pit latrines	Septic tanks
n (number of samples)	329	154	163
Mean	95.9	122.9	71.2
Standard deviation	65.9	65.9	56.3
10th quartile	24.5	33.1	20.3
Median	85.3	119.0	53.3
90th quartile	178.7	208.2	152.3

In some cities, a correlation between TS and COD has been observed (Strande *et al.* 2018; Strande *et al.* in preparation). In Lusaka, however, a strong correlation between TS and COD was not observed (R^2 = 0.57) (Annex 3). When breaking the data down between by containment type, improved correlations are observed (Figure 18). The TS to COD correlation will be revisited following further analysis of standards. Eawag will also continue to explore the data to determine whether it can be explained by other factors.

The boxplots in Figure 19 indicate that there is a trend within categories of containment type, specifically when dividing the data by unlined pit latrines, lined pit latrines (partially or fully), and septic tanks. Median and mean values are 152.5 and 146.3 g/L for unlined pit latrines, 107.7 and 118.6 g/L for partially lined pit latrines, 114.7 and 116.7 g/L for fully lined pit latrines, and 53.3 and 71.2 g/L for septic tanks respectively.

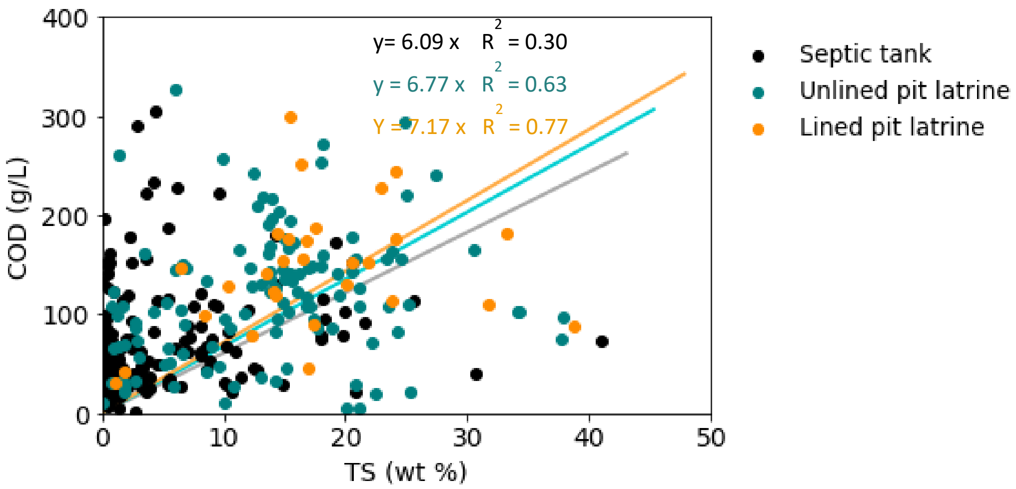

Figure 18: TS versus COD, broken down by containment type.

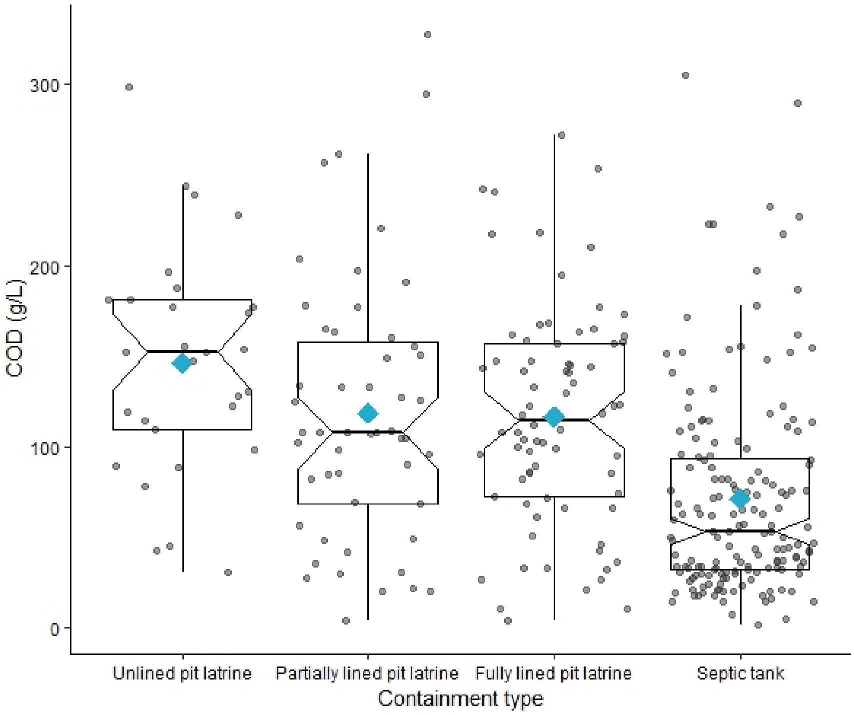

Figure 19: Boxplot COD grouped by containment type. Blue diamonds represent mean values.

There is also a significant difference for COD between households and commercial establishments (Figure 20), where medians and means are 54.9 and 76.0 g/L for commercial, and 89.6 and 98.9 g/L for household establishments.

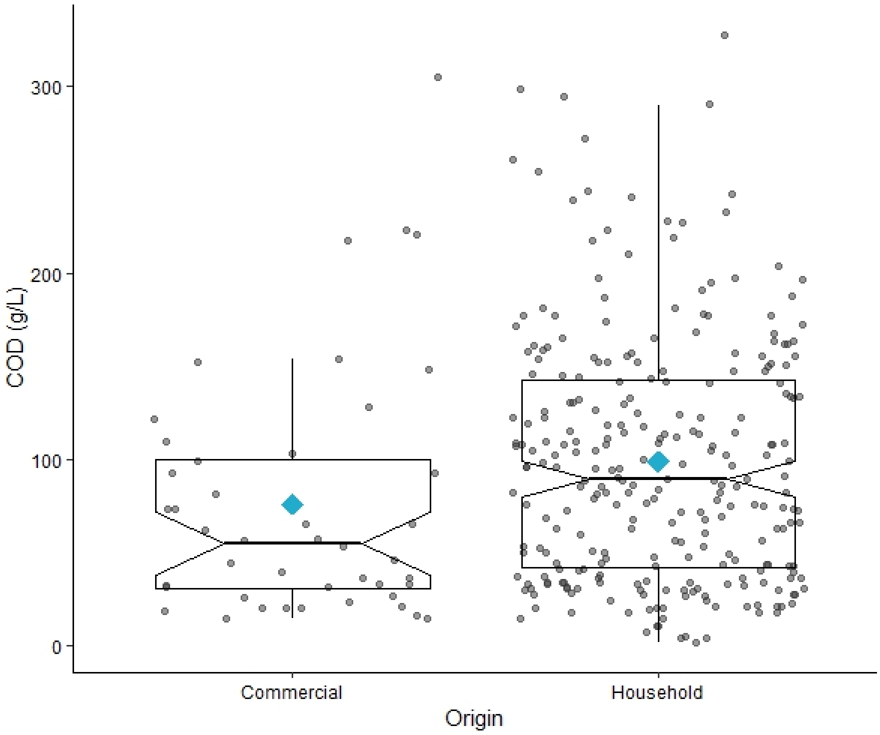

Figure 20: Boxplot COD grouped by sludge origin. Blue diamonds represent mean values.

As Figure 21 shows, a significant difference was observed in COD between 'wet' toilets (i.e. cistern flush and pour-flush), and dry toilets. This is as expected, as most wet toilets are septic tanks, which reflects the relationship between COD and containment type mentioned above.

The same seems to hold true when separating COD by water connection (Figure 22), which could also be a reflection of the relationship between COD and containment type, although the difference is not as distinct as was observed in Figure 21.

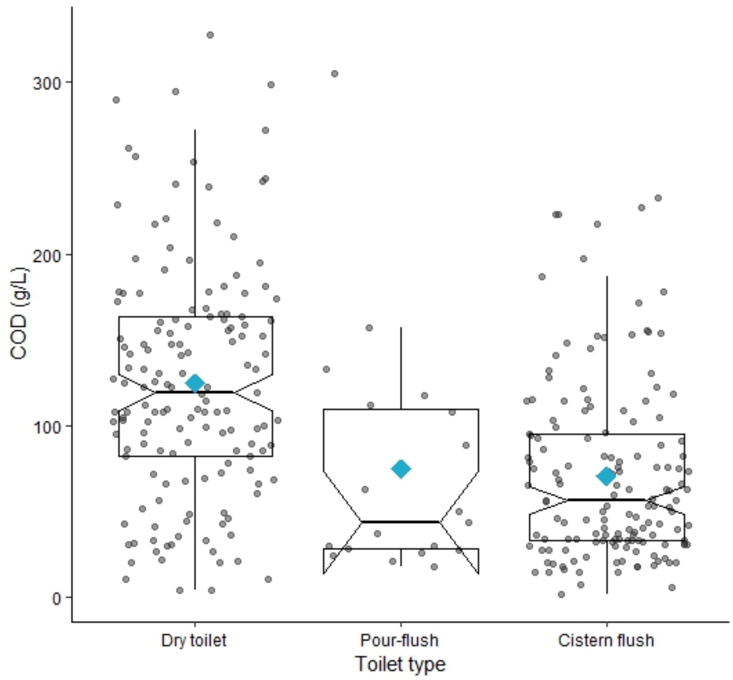

Figure 21: Boxplot COD by toilet type. Blue diamonds represent mean values.

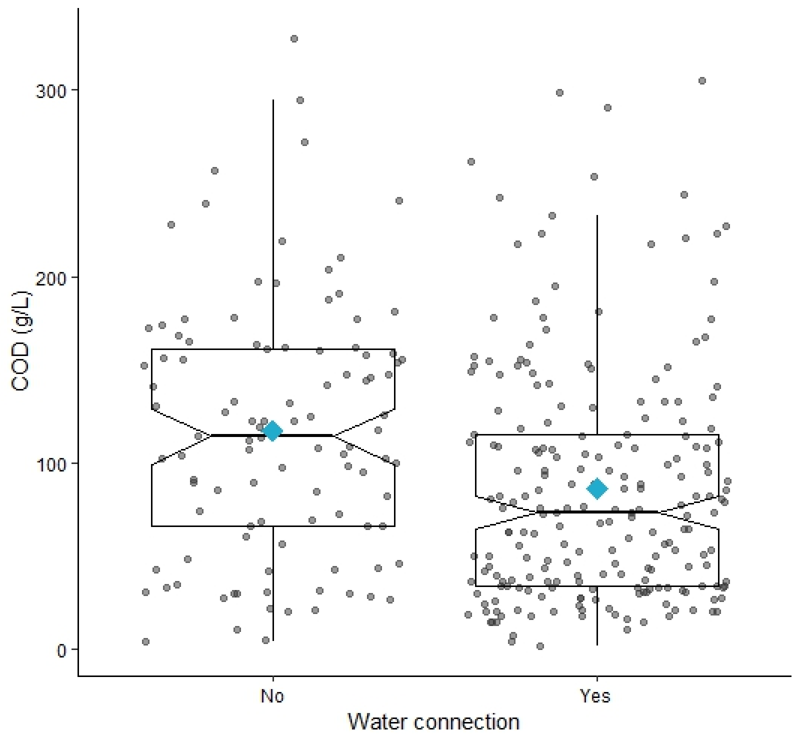

Figure 22: Boxplot COD by water connection. Blue diamonds represent mean values.

Based on the results, in general, there is a wide range of COD that should be expected for both pit latrines and septic tanks in Lusaka. As there are multiple interesting relations with various parameters for COD, we used a linear model to examine these in more detail. Containment type, water connection, and sludge origin were included in the model because from a theoretical perspective, these are likely to affect COD. The model output is presented in Table 5. It shows that containment type alone is also the most relevant parameter for COD, just like with TS. Therefore, for Lusaka it is recommended to split the data by pit latrine and septic tank separately.

Table 5: Linear model outputs for COD.

	Estimate	Standard error	P-value
(Intercept)	121.6	12.4	<2^{-16}
Water connection – *Yes*	3.9	9.3	0.68
Containment type – *Septic tank*	-54.0	8.8	3.02^{-9}
Sludge origin – *Household*	-0.9	10.7	0.93

pH

The range of pH is narrow (Table 6), with a few outliers in the acidic spectrum, and two outliers in the basic spectrum, of which one which is likely to be a measurement error. The majority of the sludge in Lusaka could be expected within the 7.1-8.0 range. No differences based on categories of collected SPA-DET data were observed.

Table 6 Descriptive statistics for pH.

	Total
n (number of samples)	421
Mean	7.6
Standard deviation	0.5
10th quartile	7.1
Median	7.7
90th quartile	8.0

Electrical conductivity (EC)

Of all the measured parameters, the strongest relationships to categories of collected SPA-DET data were observed. Table 7 displays the descriptive statistics. The results fit within the ranges reported for other cities (Appiah-Effah *et al.* 2014; Gold *et al.* 2018).

Table 7: Descriptive statistics for EC. Units are in mS/cm.

	Total
n (number of samples)	421
Mean	8.4
Standard deviation	7.1
10th quartile	1.3
Median	5.6
90th quartile	17.8

There is a significant difference for EC between pit latrines and septic tanks. Mean values for pit latrines and septic tanks are 14.2 and 2.4 mS/cm respectively. Median values for pit latrines and septic tanks are 14.4 and 1.8 mS/cm respectively. This trend has also been reported in other literature (Gold *et al.* 2018). This could be due to a higher concentration of salts (e.g. from urine) in pit latrines, and sludge in septic tanks being more diluted.

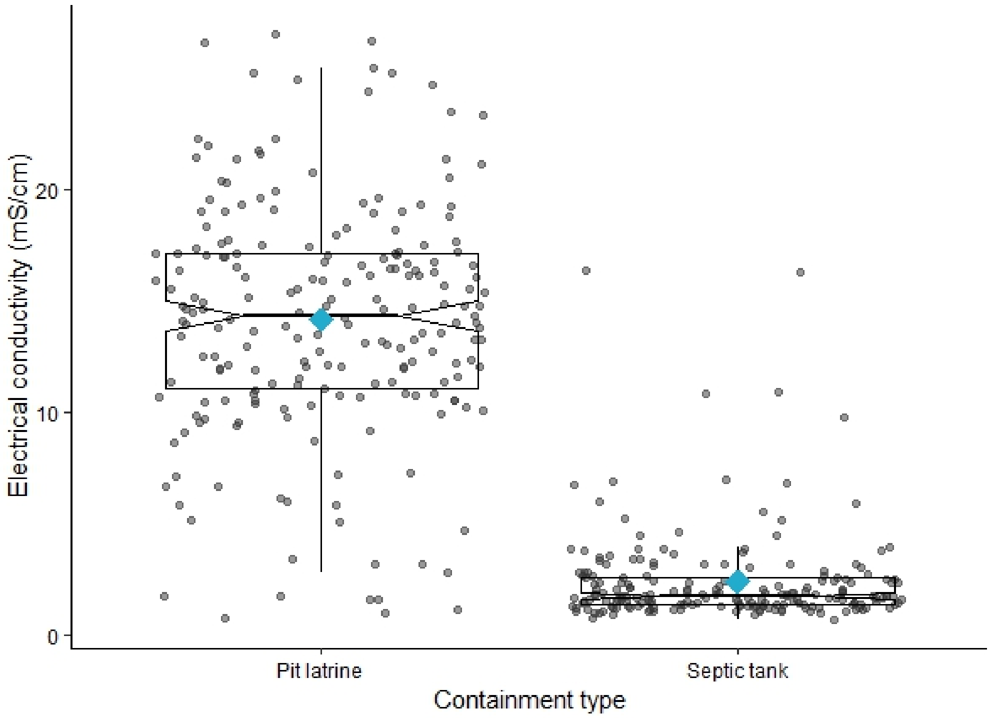

Figure 23: Boxplot EC by containment type. Blue diamonds represent mean values.

As presented in Figure 24, there is also a significant difference in EC between whether sludge comes from a household or a commercial source. Mean values are 9.2 and 3.8 mS/cm for households and commercial establishments respectively, and median values are 7.2 and 4.4 mS/cm for households and commercial establishments respectively.

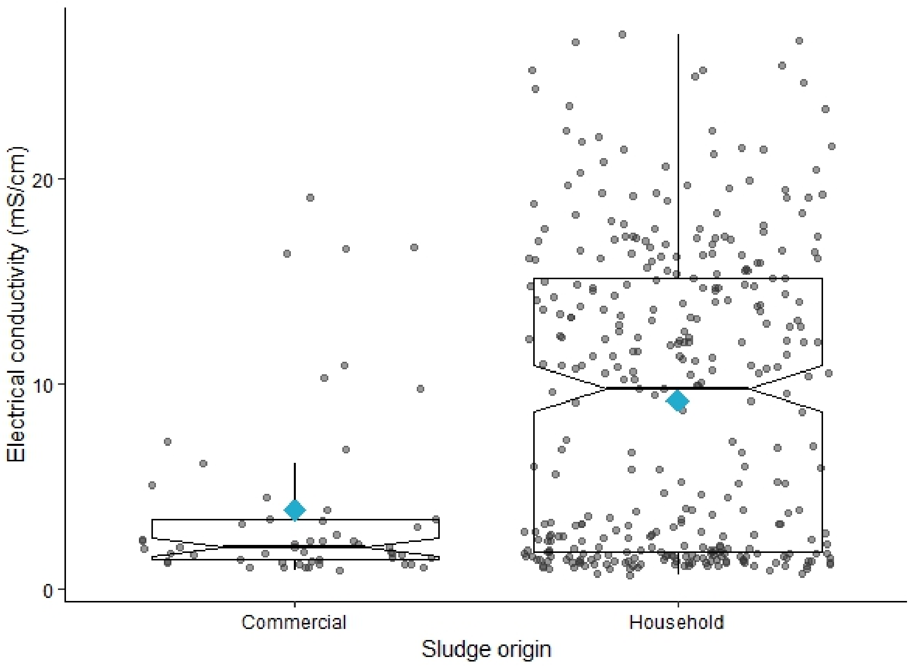

Figure 24: Boxplot EC by sludge origin. Blue diamonds represent mean values.

When splitting by toilet type, Figure 25 shows that all three categories (cistern flush, pour flush and dry toilet) are significantly different from each other. Mean values are 2.1, 7.0, and 14.3 mS/cm for cistern flush, pour flush and dry toilet respectively. Median values are 1.7, 5.1, and 14.7 mS/cm respectively.

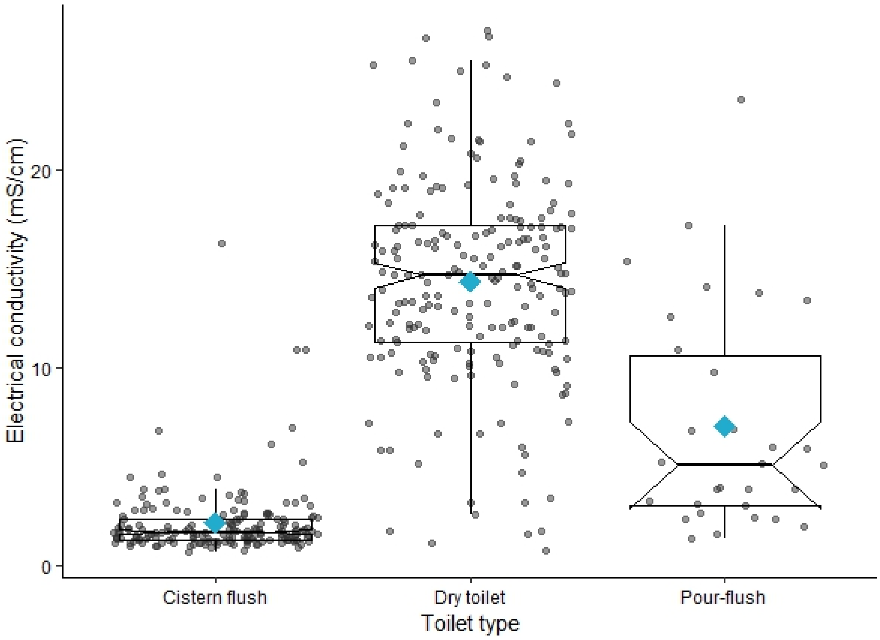

Figure 25: Boxplot EC by toilet type. Blue diamonds represent mean values.

For income, only the highest income category is significantly lower than rest, which is also a reflection of the relationship that households in the highest income category have more septic tanks (Figure 7). There was also a difference in EC when people reported a seasonal change in the sludge level (Figure 27), which can be explained by that containments that have a fluctuating sludge level are mostly pit latrines, which have a higher EC, as was already observed in Figure 23.

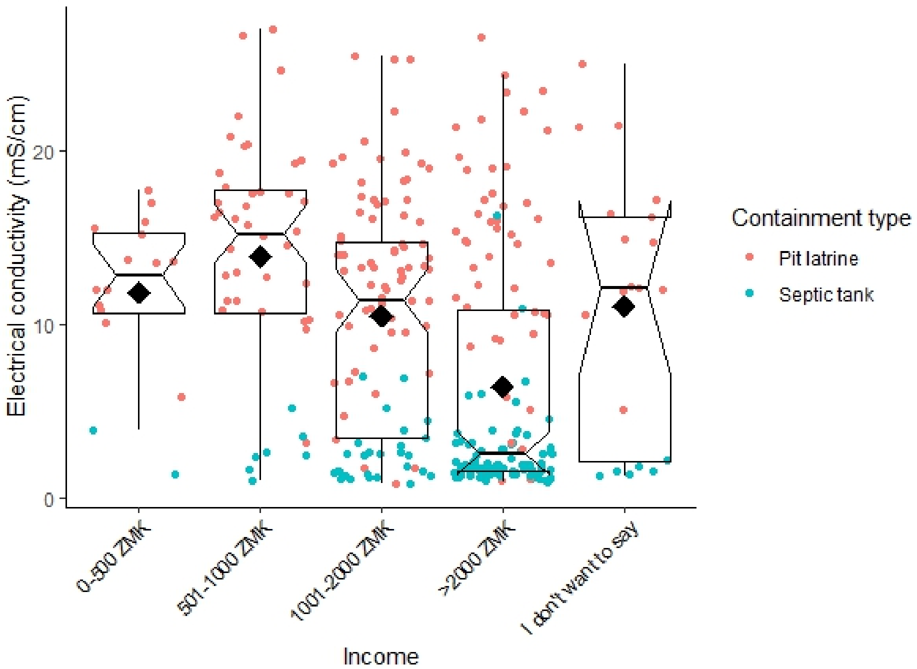

Figure 26: Boxplot EC by income. Black diamonds represent mean values.

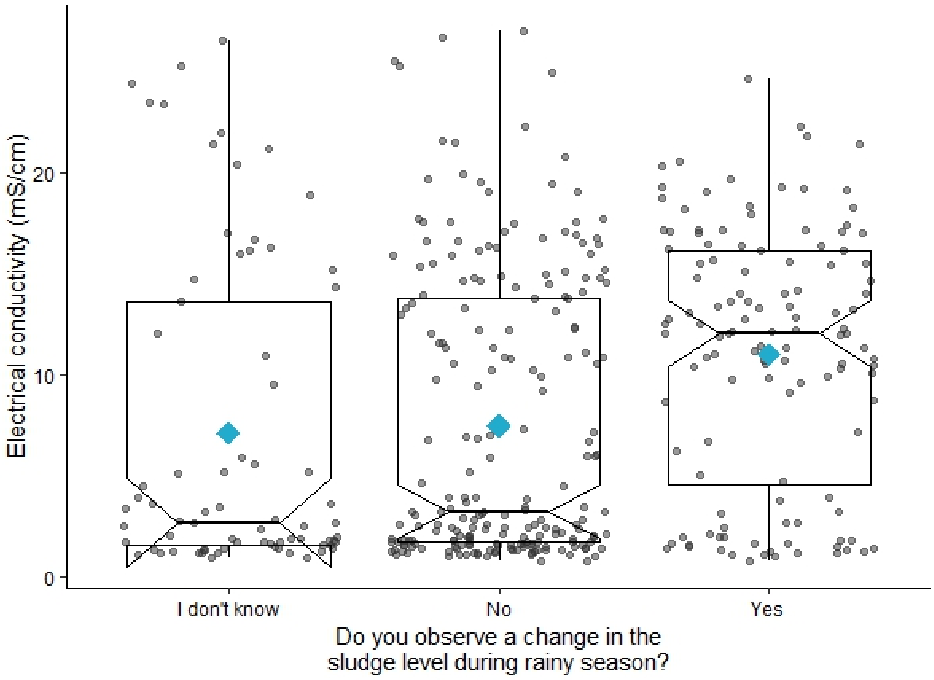

Figure 27: Boxplot EC by whether there is a change in the sludge level in the rainy season. Blue diamonds represent mean values.

EC is also significantly different for establishments with or without a water connection on the premises. This could be explained by the relationship that septic tank owners often have a water connection (Figure 8). Mean and median are 13.3 and 13.6 mS/cm for no water connection, and 5.5 and 2.2 mS/cm for establishments with a water connection on the premises.

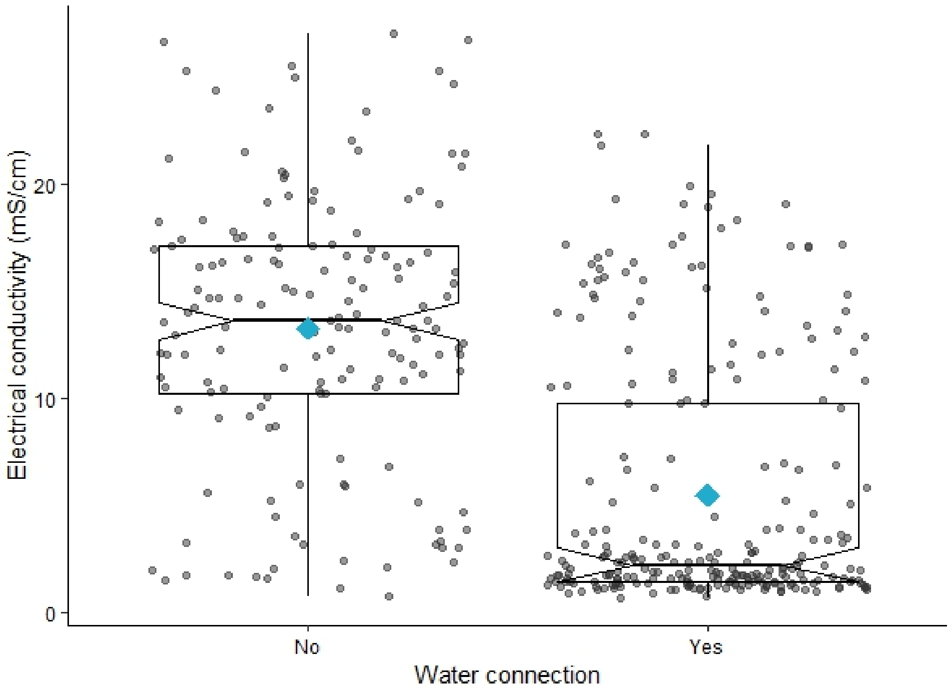

Figure 28: Boxplot EC by whether there is a water connection on the premises. Blue diamonds represent mean values.

Solid waste

Whether there was solid waste inside the containment was asked of the questionnaire respondent, and verified by the sampling team. 57% of the containments had solid waste in them; 80% of the pit latrines and 36% of the septic tanks. The sampling team most frequently noted plastics, rags/cloths, diapers, and pads. As presented in Figure 29, Figure 30, and Figure 31, TS, COD and EC seem to have a relation with whether there is solid waste in the containment. However, for each of these parameters other factors are more important than solid waste (i.e. have a stronger relationship. See paragraphs on TS, COD and EC).

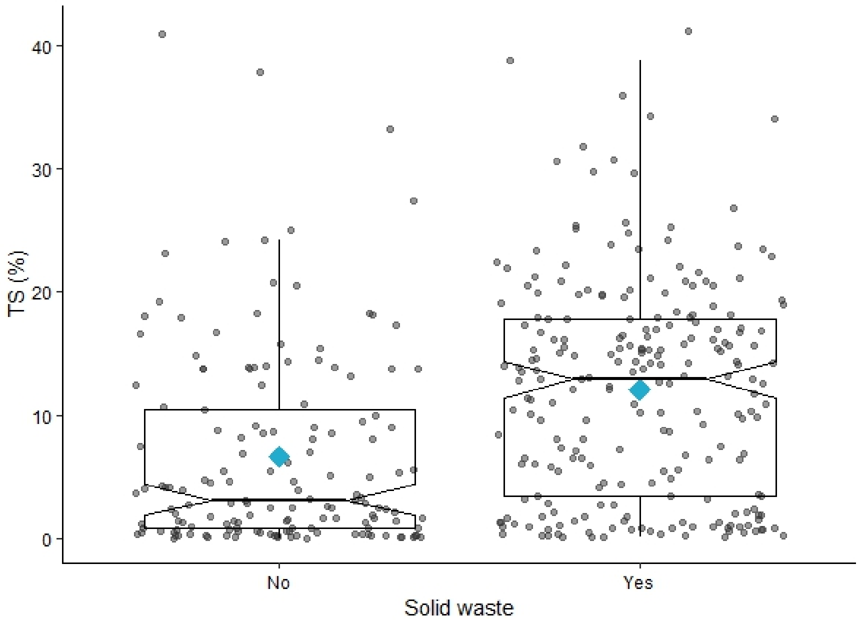

Figure 29: Boxplot TS by whether there was solid waste inside the containment. Blue diamonds represent mean values.

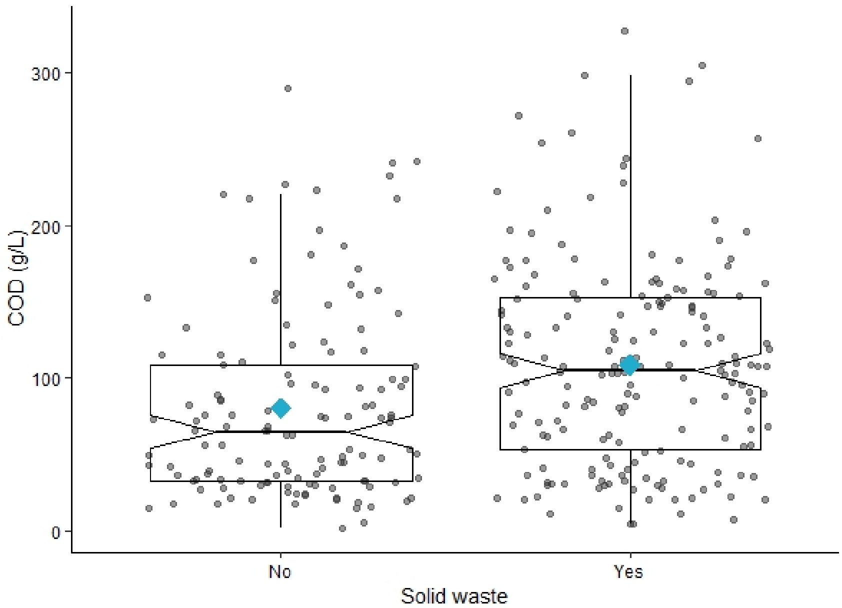

Figure 30: Boxplot COD by whether there was solid waste inside the containment. Blue diamonds represent mean values.

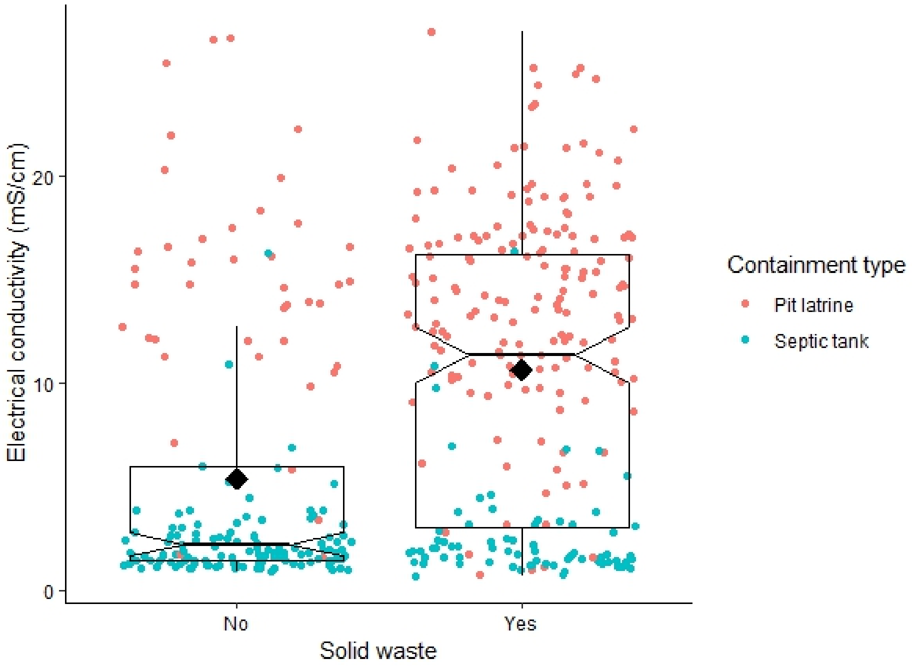

Figure 31: Boxplot EC by whether these was solid waste inside the containment. Black diamonds represent mean values.

Spatial analysis

The spatial distribution of the categories based in the SPA-DET data were analyzed. There are pockets within the city where it is less likely that people have a water connection on the premises (Figure 32). From observation these are around Kanyama, George, Chazanga and Mutendere.

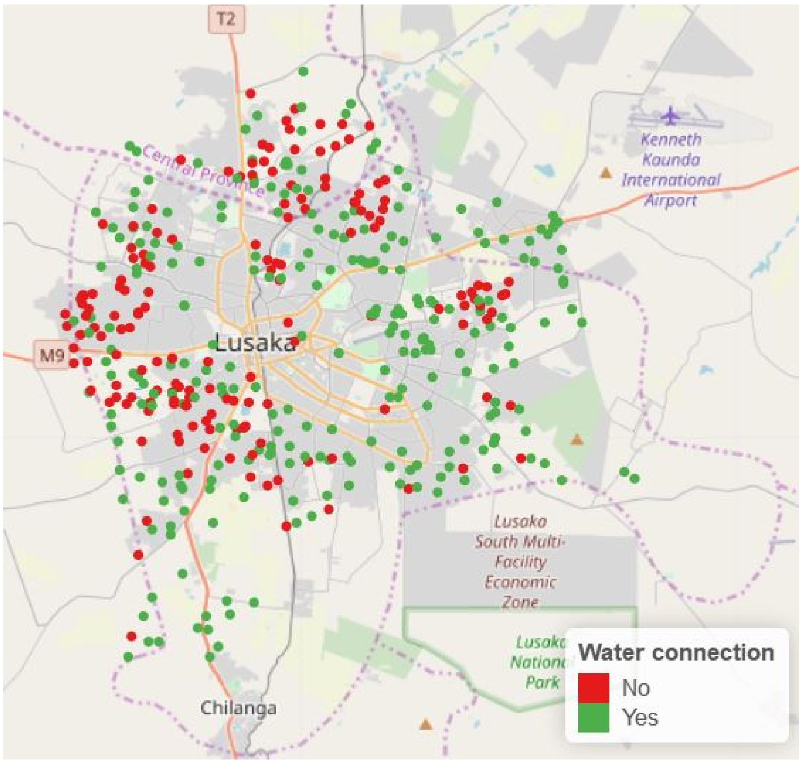

Figure 32: Spread of samples by whether there is a water connection on the premises.

The same areas are also the areas where the sludge level is varying according to the season (Figure 33). Specifically in the western part of the city around Kanyama and George is where sludge levels are varying. This is unsurprising, as this is the dolomite area, where historically this change in sludge level has been observed. However, not all containments in these areas have varying sludge levels, as is indicated in Figure 33.

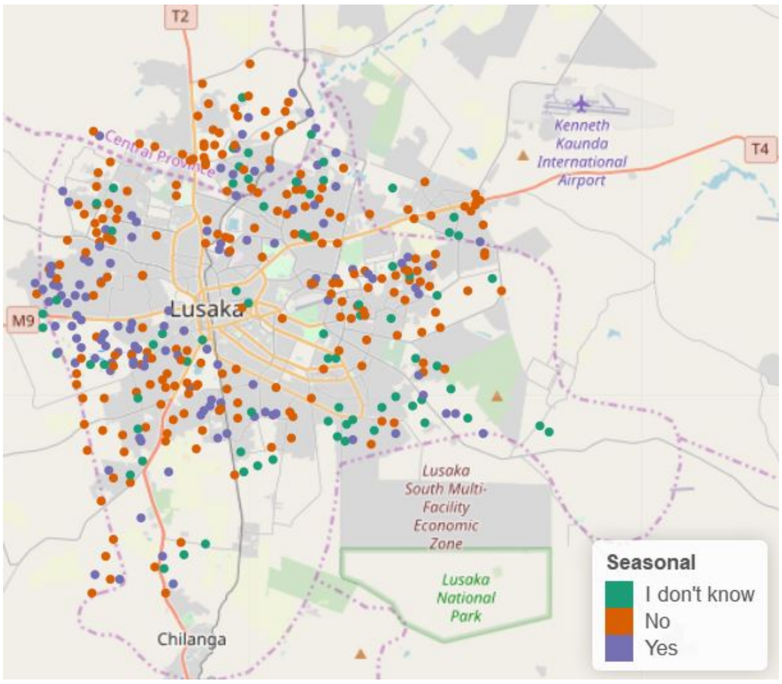

Figure 33: Spread of samples by whether a change in sludge level is observed during the rainy season.

Presented in Figure 34 is a distribution of the sampling team's observations of solid waste in containments. A clear pattern is not distinguishable. More maps with spatial distributions of different parameters that did not show patterns are provided in Annex 3. All maps in this report can be zoomed in for closer analysis using the provided R code.

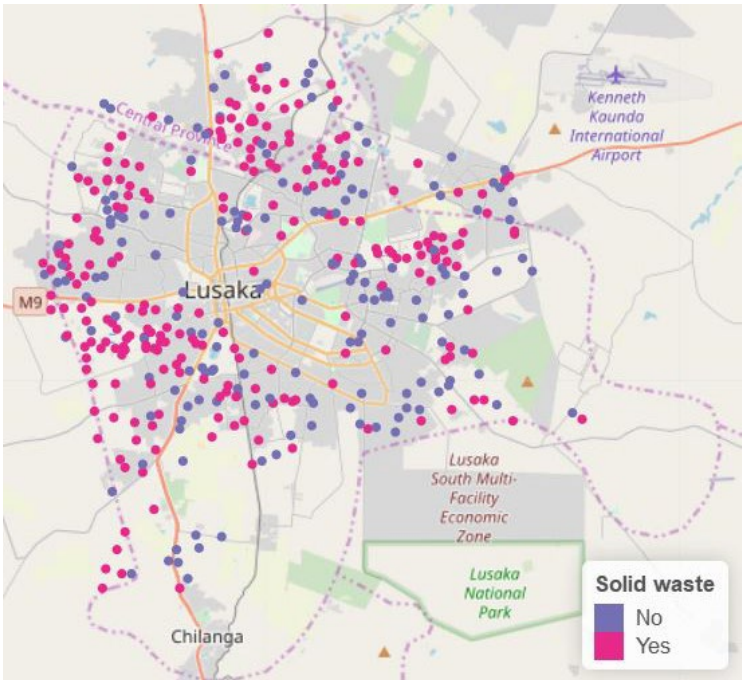

Figure 34: Spread of samples by whether there is solid waste inside the containment.

Quantities

Faecal sludge accumulation rate

In Table 8 the descriptive statistics for faecal sludge accumulation rate are presented. From observation of the data, it seems to be the case that containments that were emptied recently have a higher accumulation rate. This has been observed elsewhere; results from Kampala and Thailand show that containments that were emptied frequently, <1year, had higher accumulation rates (Strande *et al.* 2018). In Kampala, containments with a high accumulation rate were often industrial/commercial tanks without an outlet. In contrast, in Lusaka, most of the containments with a high accumulation rate are households. To explore this relationship further, values from containments that were emptied less and more than one year ago are also reported separately in Table 8 and Figure 35. Even when calculating the accumulation rate by month instead of by year the same relationship remains. A hypothesis to explain the significant difference could be that containments that were emptied recently are also the containments that are emptied more frequently, because their accumulation rate is high.

Table 8: Descriptive statistics for total faecal sludge accumulation rate, and faecal sludge accumulation rate of containments that were emptied less and more than one year ago. NAs were left out for the category breakdown. Units are in L/cap·year.

	Total	Emptied <1 year ago	Emptied >1 year ago
n (number of samples)	380	95	285
Mean	128	336	58
Standard deviation	330	575	131
10^{th} quartile	5	29	4
Median	33	158	22
90^{th} quartile	317	686	131

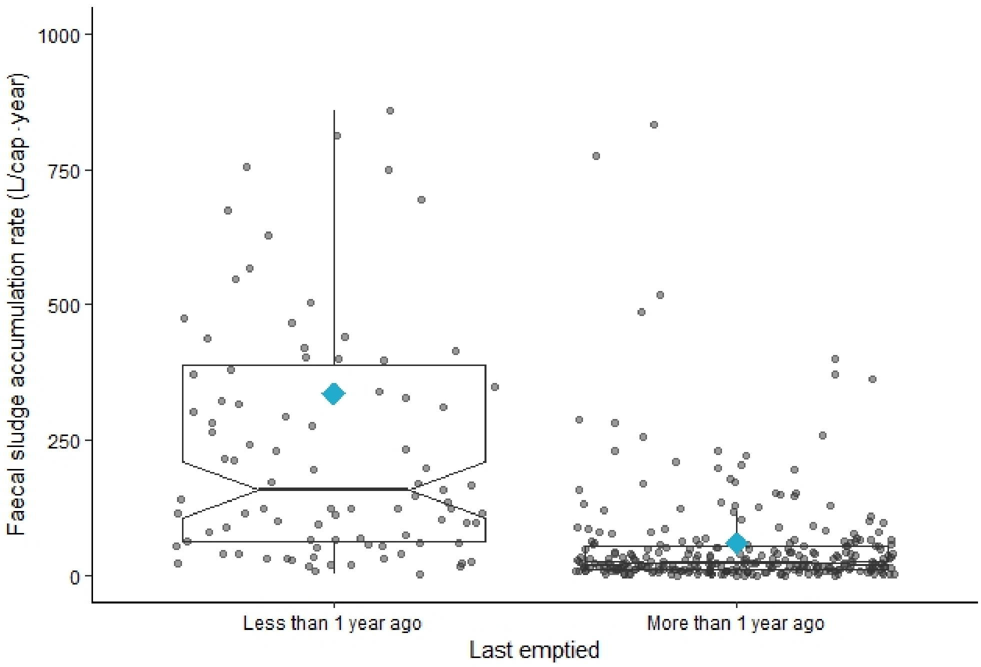

Figure 35: Boxplot faecal sludge accumulation rate by whether the containment was emptied recently (less than 1 year ago) or longer ago (more than 1 year ago). Blue diamonds represent mean values. The y-axis is capped at 1000 L/cap·year to improve readability, but actually runs until 4000 L/cap·year.

There is significant difference between faecal sludge accumulation rate for pit latrines and septic tanks. Accumulation rate is higher in septic tanks, with an mean rate of 190 L/cap·year, and median of 58 L/cap·year. In pit latrines, mean is 59 L/cap·year and median is 23 L/cap·year. An explanation could be that septic tanks are more likely to receive more water than pit latrines. It is also worth noting that containments that were emptied recently are both latrines and septic tanks.

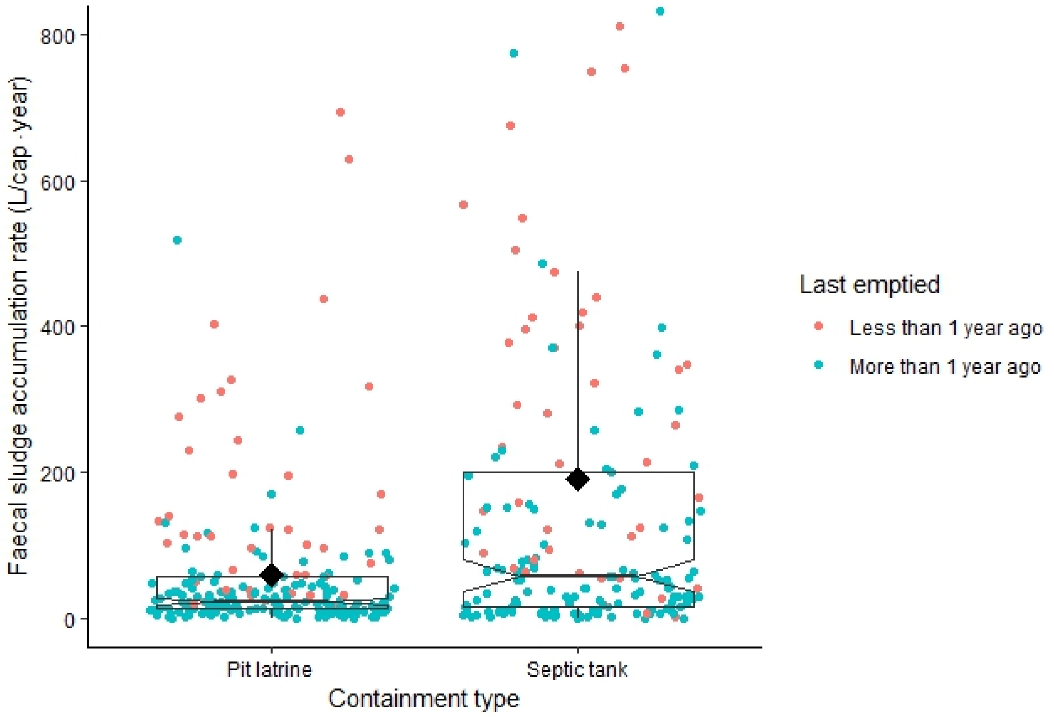

Figure 36: Boxplot faecal sludge accumulation rate by containment type. Black diamonds represent mean values. The y-axis is capped at 800 L/cap·year to improve readability, but actually runs until 4000 L/cap·year.

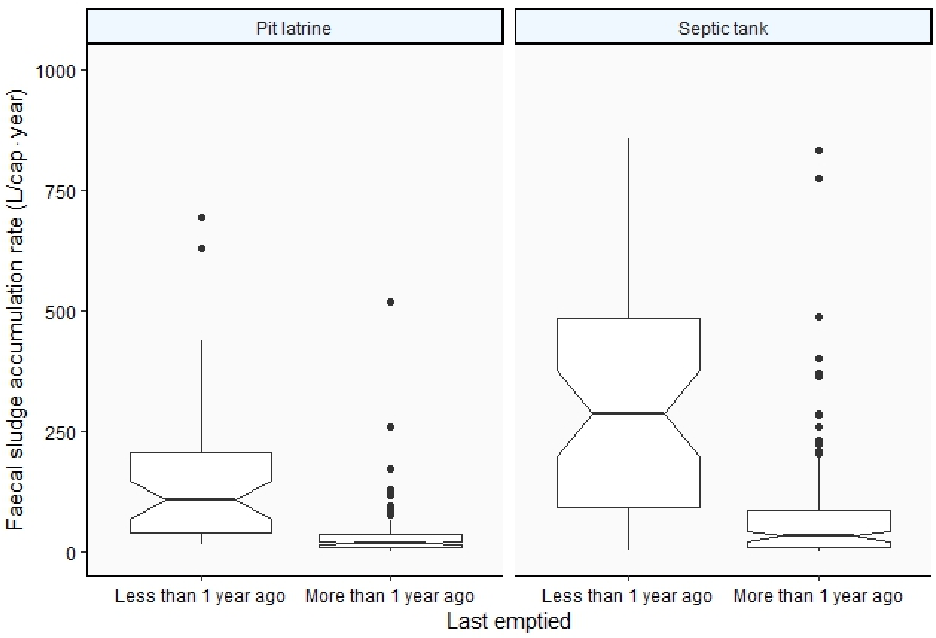

Figure 37: Boxplot faecal sludge accumulation rate by containment type, divided by whether it was emptied more or less than 1 year ago. The y-axis is capped at 1000 L/cap·year to improve readability, but actually runs until 4000 L/cap·year.

Table 9: Table showing the mean faecal sludge accumulation rate (L/cap·year) by containment type and when it was last emptied.

	Last emptied (L/cap·year)	
Containment type	<1 year ago	>1 year ago
Septic tanks	692	92
Pit latrines	270	32

Further analysis, breaking faecal sludge accumulation rate down by type of containment and when they were last emptied still shows a significant difference (Figure 37). This appears to be a useful way of thinking about faecal sludge accumulation rate. The values are summarized in Table 9. This table can of course also be made for median values.

Other parameters did not show significant differences for faecal sludge accumulation rate. Unexpectedly, geology type did also not show a significant difference for faecal sludge accumulation rate.

Sludge blanket accumulation rate

Sludge blanket accumulation rates were only calculated for containments where the core sampler was used and a settled sludge layer could be measured (n=180). The variation within the calculated sludge blanket accumulation rates is enormous, with a standard deviation of more than twice the mean (Table 10). Upon examination of the data, the very high values are from (commercial) containments with many users (>100) that were recently emptied. The very low values are also from commercial containments with many users. Sludge blanket accumulation rate does not show a relationship with containment age, however, there is a significant difference between containments that were emptied recently and containments that were emptied more than 1 year ago (Figure 38 and Table 10), just like for faecal sludge accumulation rate. In Figure 39 and Figure 40 the sludge blanket accumulation rate for categories of sludge origin and for whether there was a seasonal change in sludge level are shown. However, neither of these has any predictive value, and just show one way of looking at the distribution of this data.

Table 10: Descriptive statistics for sludge blanket accumulation rate. Units are in L/cap·year.

	Total	Emptied <1 year ago	Emptied >1 year ago
n (number of samples)	180	53	127
Mean	83	206	32
Standard deviation	175	274	59
10^{th} quartile	2	19	1
Median	23	111	12
90^{th} quartile	205	506	92

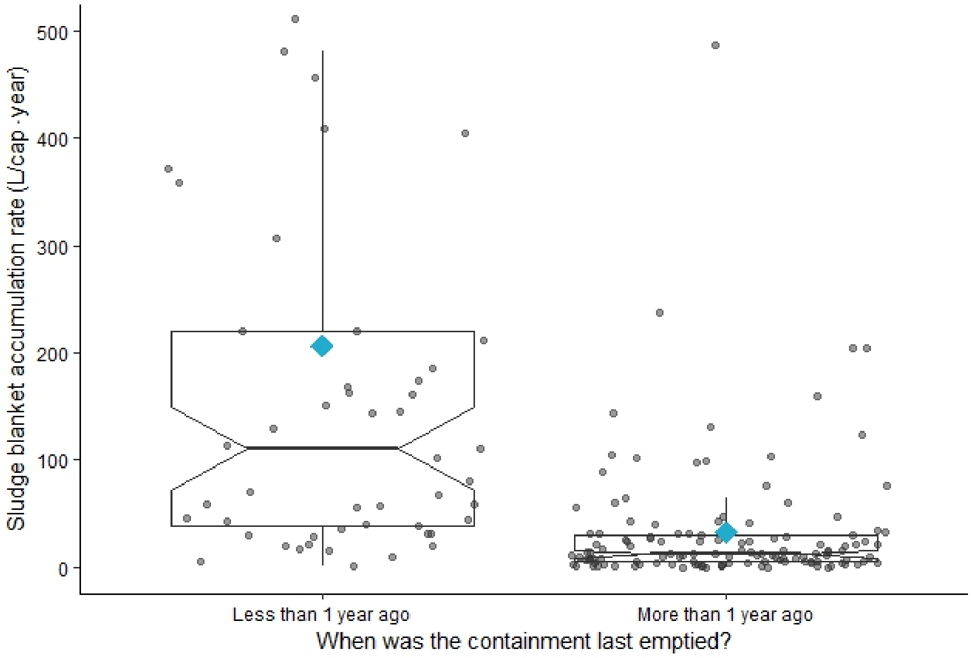

Figure 38: Boxplot sludge blanket accumulation rate by whether the containment was emptied less or more than 1 year ago. The y-axis is capped at 500 L/cap·year to improve readability, but actually runs until 1500 L/cap·year.

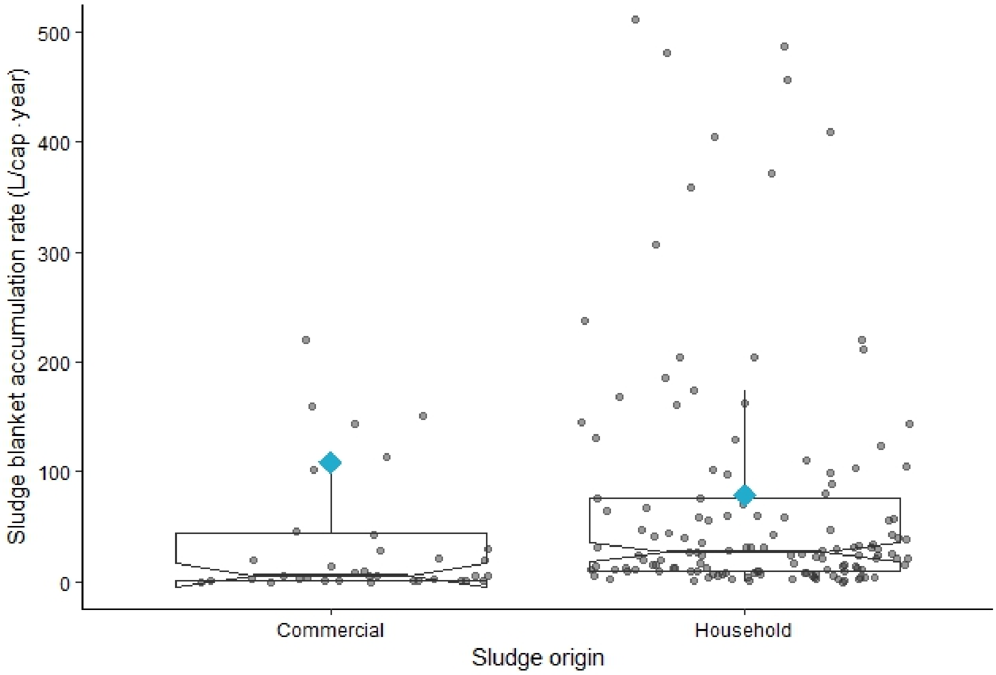

Figure 39: Boxplot sludge blanket accumulation rate by sludge origin. The y-axis is capped at 500 L/cap·year to improve readability, but actually runs until 1500 L/cap·year.

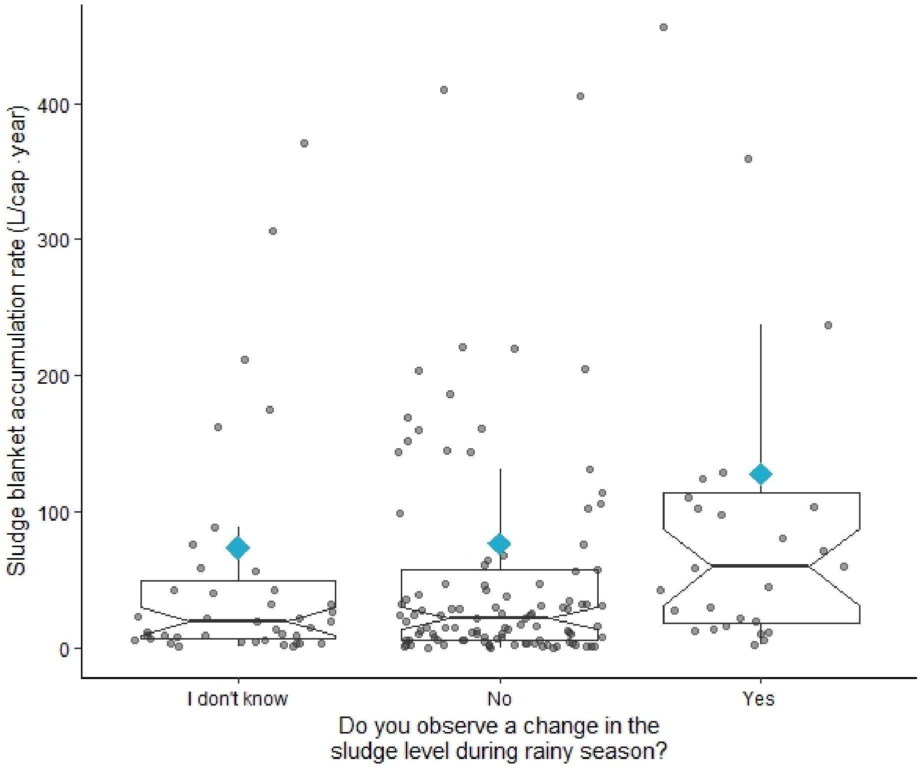

Figure 40: Boxplot sludge blanket accumulation rate by whether a change in sludge level is noticeable during rainy season. Blue diamonds represent the mean. The y-axis is capped at 450 L/cap·year to improve readability, but actually runs until 1500 L/cap·year.

Conclusions

It is planned that at least two new faecal sludge treatment plants will be constructed in Lusaka in the coming years. For semi-centralized to decentralized treatment plants, the Q&Q results should be evaluated specifically by the served area to evaluate differences based on categories of collected SPA-DET data. Rates of accumulation in this study are based on total amounts that accumulate by type of containment. Loadings for the treatment plants will have to include estimates for the total number of containments in the served area. Based on the total number, the emptying frequency, and how sludge will be collected and transported then also needs to be taken into account. For example, the results indicate that containments that are emptied more frequently have much higher rates of accumulation, as summarized in Table 11. Large differences are also seen between pit latrines and septic tanks, both in accumulation rates and concentrations of TS and COD. For the operation of treatment plants, it will also be important to keep in mind not only average values to estimate loadings, but also the large variation of Q&Q of faecal sludge that will arrive to treatment on a daily basis.

Table 11: Table summarizing the most interesting results for quantities and qualities in Lusaka.

	Faecal sludge accumulation rate		Qualities	
Containment type	Last emptied <1 year ago (L/cap·year)	Last emptied >1 year ago (L/cap·year)	TS (% w/w)	COD (g/L)
Septic tanks	692	92	4.8	71.2
Pit latrines	270	32	14.7	122.9

In the future, projections for total accumulated faecal sludge, together with what is being delivered to treatment, can be used to inform the gap that still requires management solutions. A better understanding of accumulation rates could also be used to make recommendations for emptying frequency, and to design plans for the management of emptying services.

Provided in this report are results of the Q&Q study by categories of collected SPA-DET data. In the coming months, the results will be further analyzed by Eawag, evaluating the potential for more advanced approaches for data analysis to develop a further understanding of the relations that were observed. This will be useful for the targeted design of any future sampling to refine estimates of Q&Q of sludge, and to shape applied research on how to improve treatment. Eawag will also provide technical backstopping for the application and further use of values obtained in this study. Further key lessons learned during the implementation of this study include:

- Many of the results obtained correspond with expert experience. However, previously the assumptions could not be quantified with actual data.
- Projected loadings for septic tanks and pit latrines should be estimated separately based on containment type, as there is a significant difference for almost all measured parameters.
- Results confirm that higher-income households (>2000 ZMK) have more septic tanks, and lower-income more pit latrines. In the future, the relationship could be refined based on more accurate demographic data including household income.
- To estimate accumulation rates, it is useful to provide separate estimates for containments that have been emptied less than 1 year ago and more than 1 year ago. As has been observed in other cities, these results could indicate that containments that are more frequently emptied have higher accumulation rates.
- Differences were observed between Q&Q of sludge from households and commercial sites. To further understand differences between categories of commercial sites, it will be useful to sample more schools, public toilets, office buildings, and malls.
- Historically, accumulation rates for septic tanks have been based on estimates for sludge blanket accumulation. However, in practice most septic tanks are not operating as intended, so that the sludge blanket varies a lot over time depending on the operating conditions. Therefore, total faecal sludge accumulation rate (including emptying frequency) are more useful for designing loadings for treatment plants.

Figure 41: The sampling team celebrating the last collected sample, number 421.

Acknowledgements

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Annexes

Annex 1 – Questionnaire questions

Is the establishment accessible for sampling?
If no, why not?
Sample identification number (###-Team-YYYYMMDD)
Local area name
Type of establishment
Optional additional information to type of establishment
How many residents live in the household?
Building type
Optional additional information to building type
Roof type
Optional additional information to roof type
Primary occupation of the head of the household
Highest educational qualification
Monthly income level
Type of containment
Does this septic tank have one or more baffles?
Is there an outflow?
If yes, where does the outflow go to?
What type of toilet(s) feed into this containment system?
Number of users
Type of anal cleansing material
Is there solid waste in the containment?
If yes, what type(s) of solid waste?
Do you add anything to the containment (for example ash, bio additives, enzymes)?
Type of wastewater entering the containment
Age of the system
Do you notice a change in the sludge level in your system between the wet and dry seasons?
Is there a water connection on the premises?
When was the system last emptied?
Was it fully emptied at that time?
GPS location
Take a picture of the toilet superstructure
Take a photo of the building

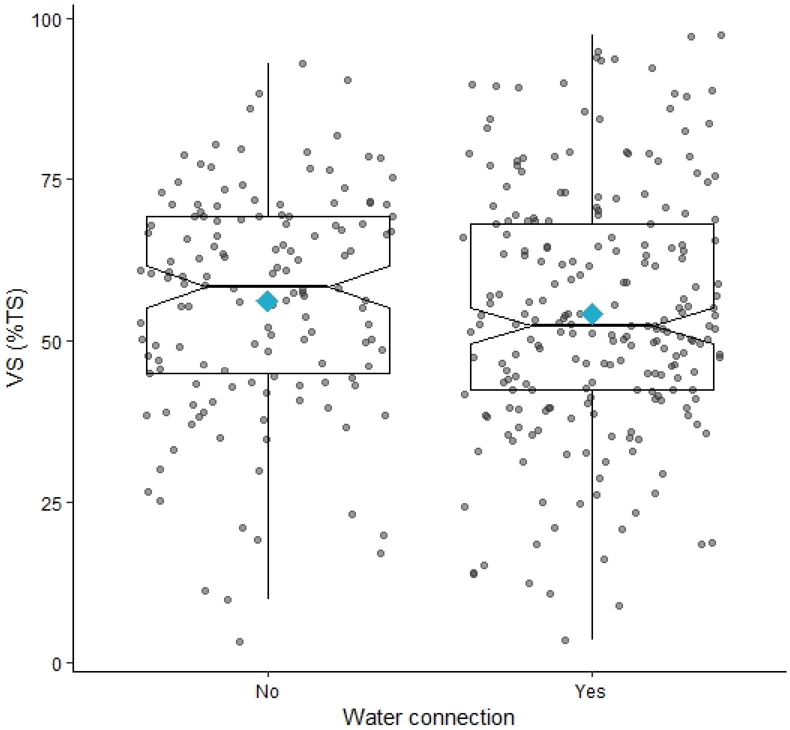
Annex 2 – Sampling team recording sheet

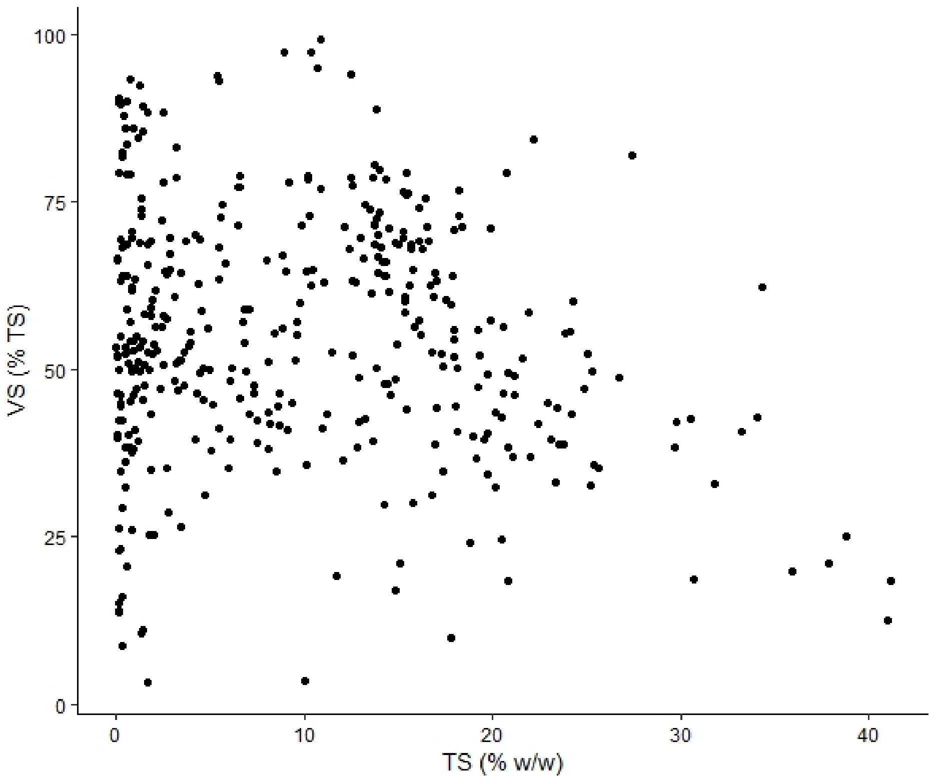
UNIVERSITY OF ZAMBIA EWAGA LUSAKA Q&Q PROJECT

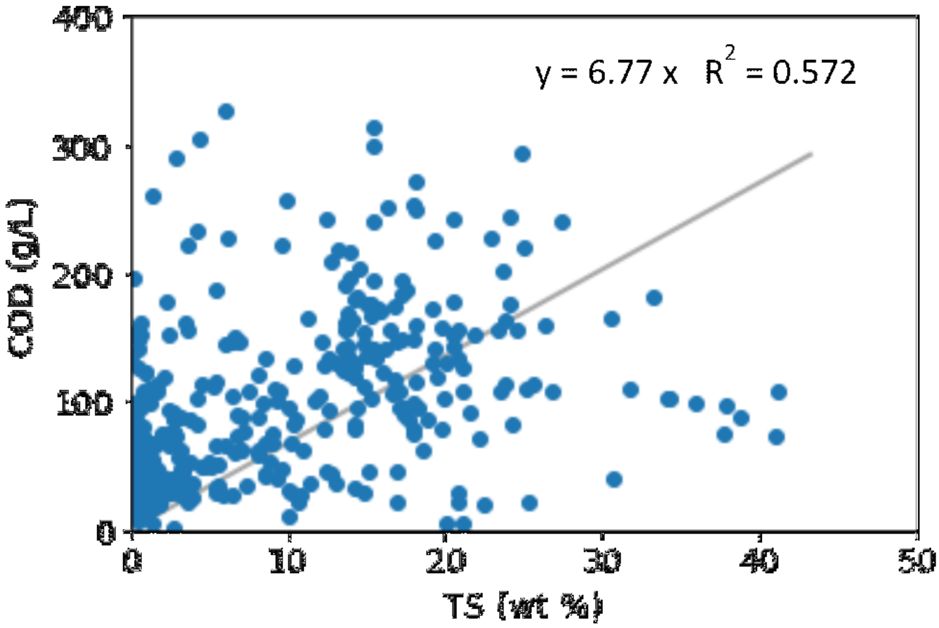
Q & Q Field Forms for data Entry

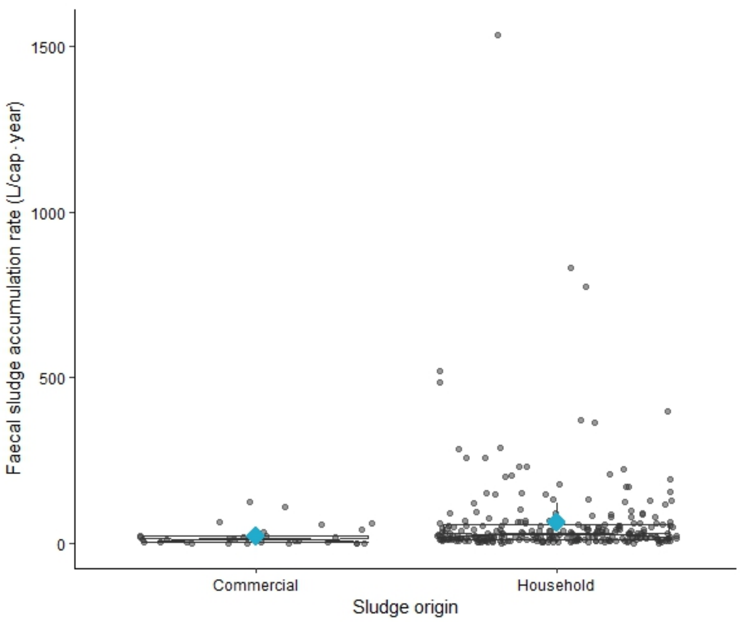
	DETAILS	
1.	Sample ID	
2.	Containment Type	
3.	Total Depth of the Tank (Probe)	
4.	Total Depth of the Sludge (Probe)	
5.	Length of the Containment measuring tape	
6.	Width of the Containment measuring tape	
7.	Total Depth of the Sludge (core)	
8.	Total Depth of the Settled Sludge (core)	
9.	Distance Top of the tank to sludge (Volaser)	
10.	Area/Circumference (Volaser)	
	Check if: line 9 + line 4 = +/- 10% of line 3	
	Check if: line 9 + line 7 = +/- 10% of line 3	
	Comment: Estimated volume if the Volaser doesn't work, anything unusual e.g. too full or too empty, why? Lots of trash? Etc. etc.	
At the End of the day send the pictures of Field book to WhatsApp group!!!		

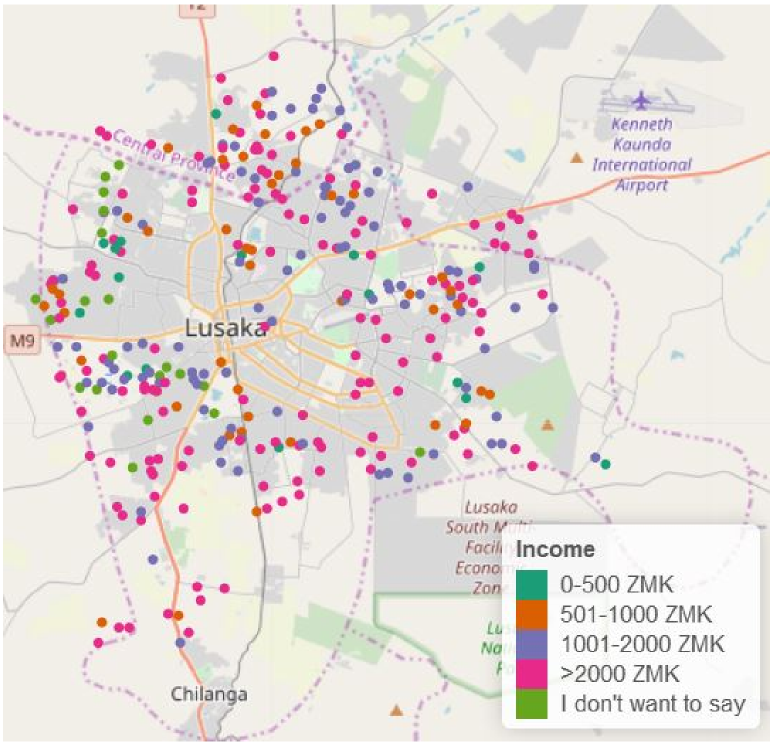
Annex 3 – Additional results from data analysis

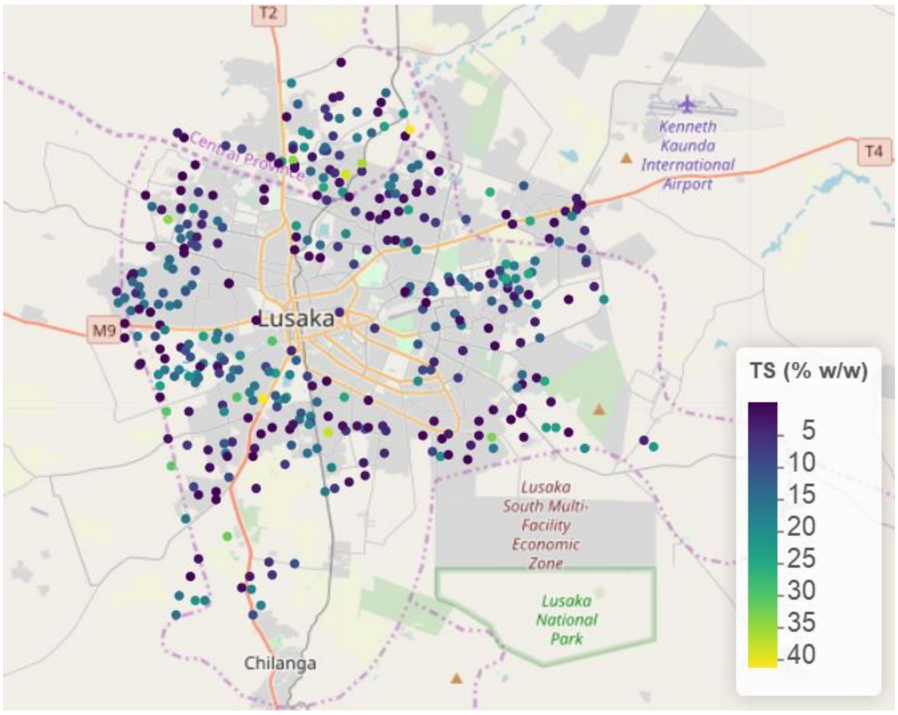





y = 6.77 x R2 = 0.572
COD (g/L)
TS (wt %)
0
100
200
300
400
0
10
20
30
40
50

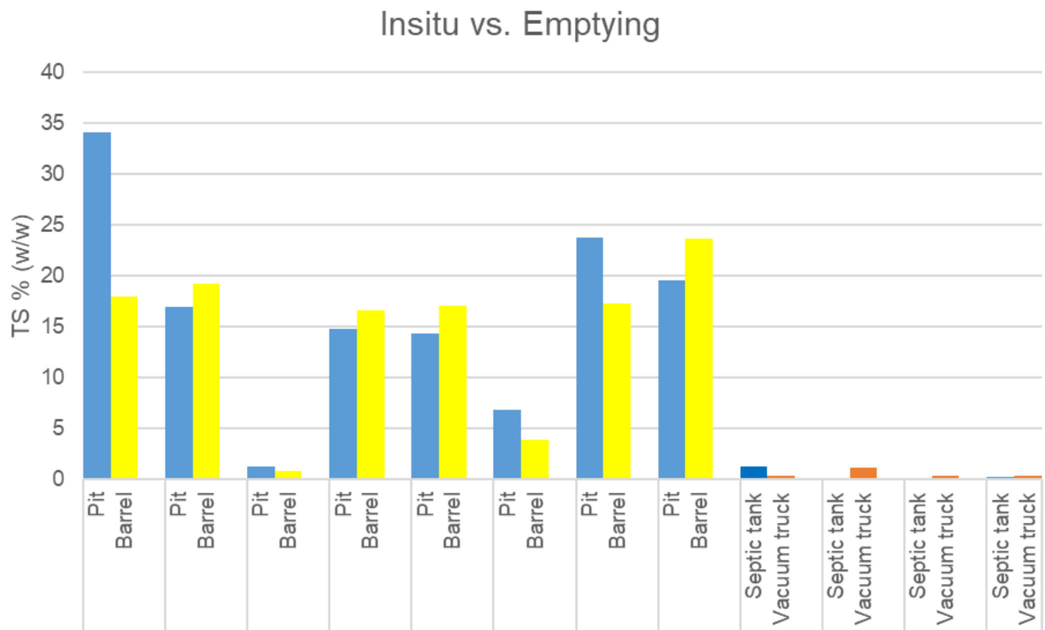

Faecal sludge accumulation rate (L/cap · year)
0
500
1000
1500
Commercial
Household
Sludge origin


Kenneth Kaunda International Airport
Central Province
M9
Lusaka
Lusaka South Multi-Facility Economic Zone
Chilanga
Income
0-500 ZMK
501-1000 ZMK
1001-2000 ZMK
>2000 ZMK
I don't want to say

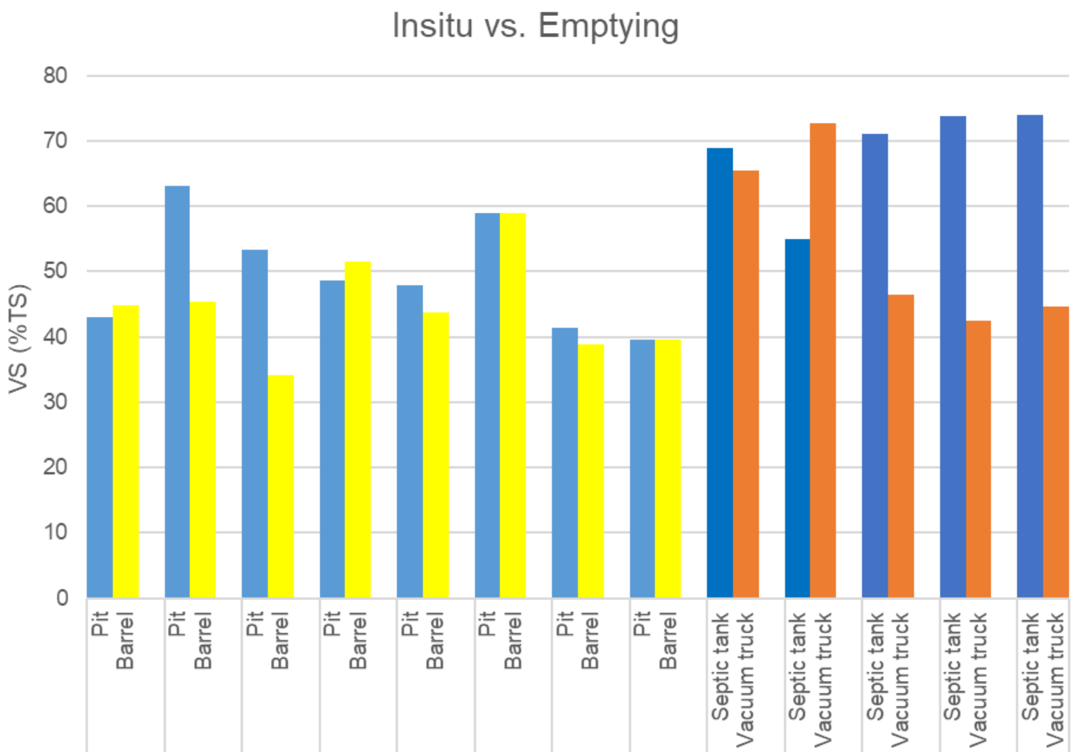

T2
Kenneth Kaunda International Airport
T4
Central Province
M9
Lusaka
Lusaka South Multi-Facility Economic Zone
Lusaka National Park
Chilanga
TS (% w/w)
5
10
15
20
25
30
35
40

Annex 4 - QA/QC in situ versus ex situ sampling

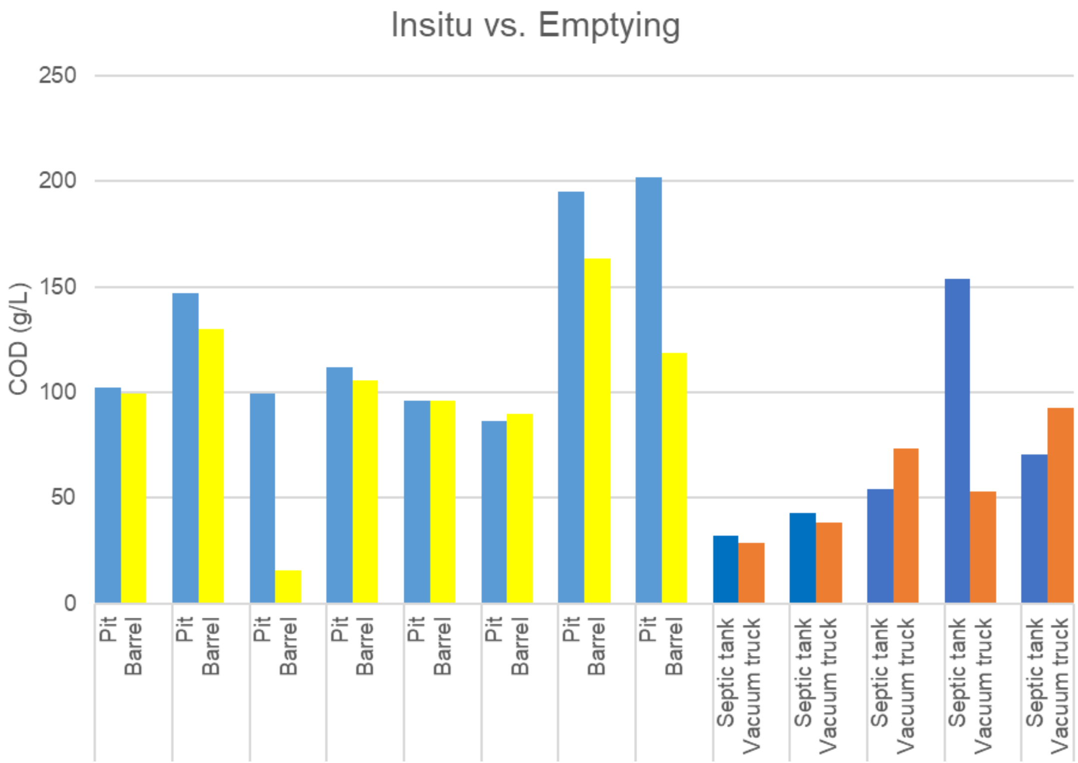
Bar graphs for each parameter, comparing in situ sampling with ex situ sampling (during emptying).



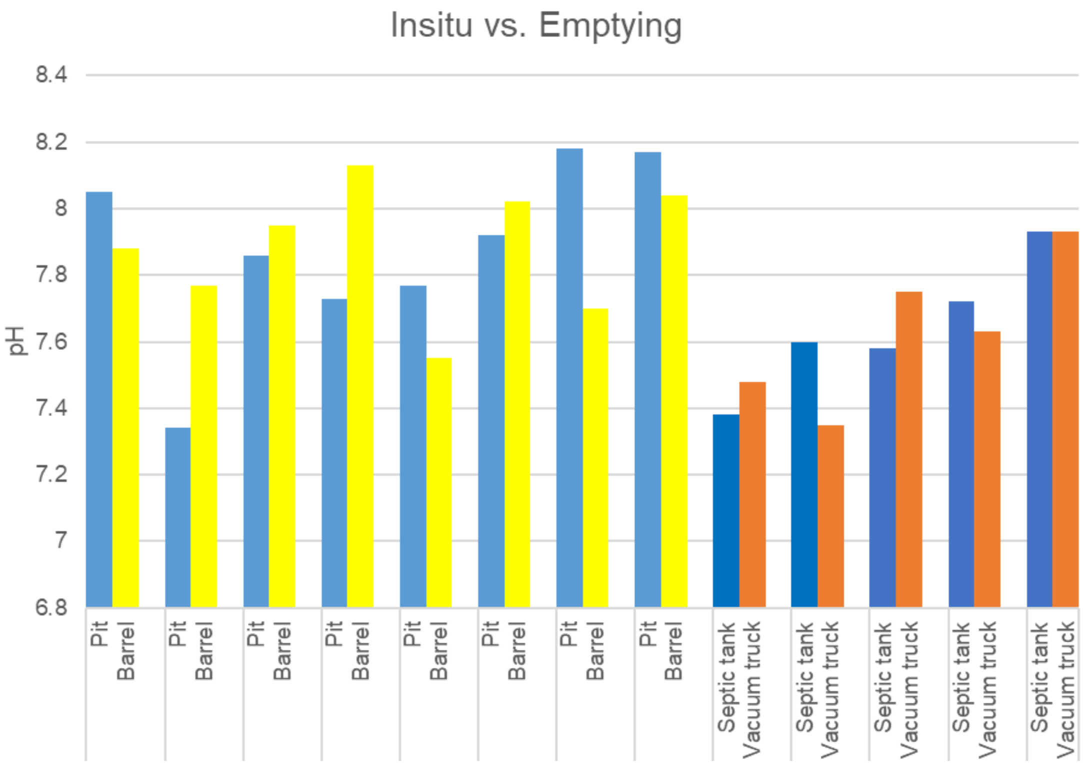
Bar graph comparing insitu sampling (pit or septic tank) versus samples collected during emptying operation (exsitu) (barrel or vacuum truck) for TS. Each bar pair on the x-axis represents one containment. One of the five septic tank/vacuum truck pairs was removed due to measurement error.



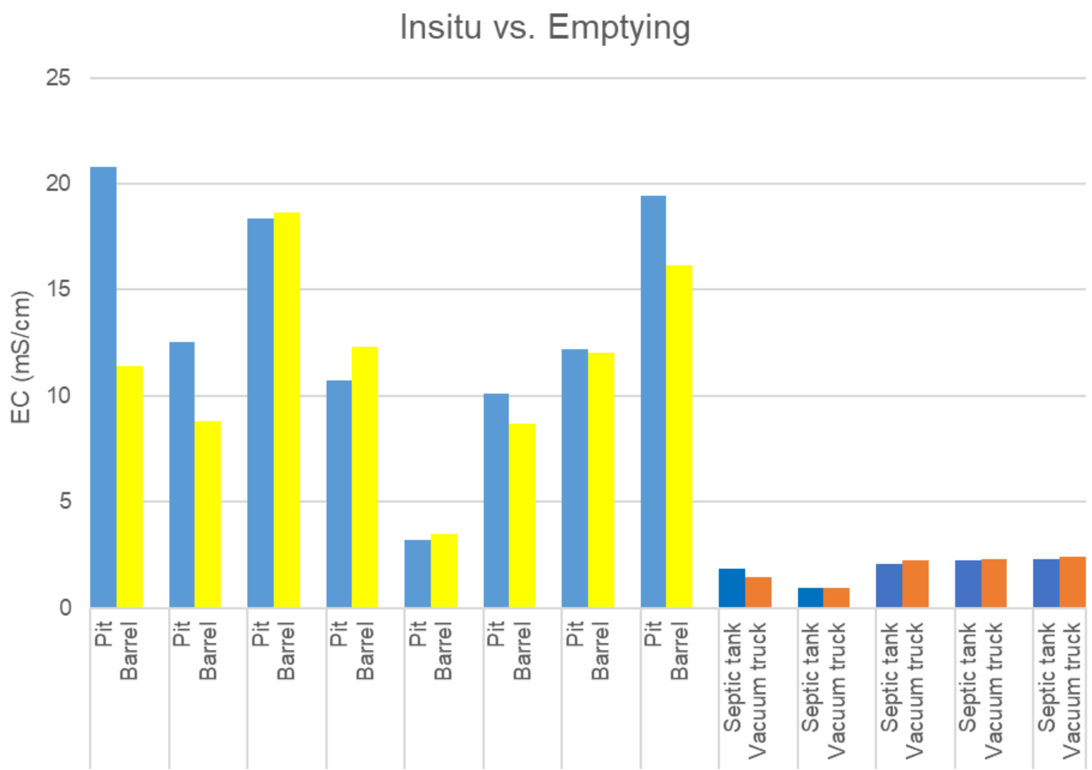
Bar graph comparing insitu sampling (pit or septic tank) versus samples collected during emptying operation (exsitu) (barrel or vacuum truck) for VS. Each bar pair on the x-axis represents one containment.



Bar graph comparing insitu sampling (pit or septic tank) versus samples collected during emptying operation (exsitu) (barrel or vacuum truck) for COD. Each bar pair on the x-axis represents one containment.



Bar graph comparing insitu sampling (pit or septic tank) versus samples collected during emptying operation (exsitu) (barrel or vacuum truck) for pH. Each bar pair on the x-axis represents one containment.



Bar graph comparing insitu sampling (pit or septic tank) versus samples collected during emptying operation (exsitu) (barrel or vacuum truck) for EC. Each bar pair on the x-axis represents one containment