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Research article

Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions

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ABSTRACT

Sanitation access in urban areas of low-income countries is provided through unstandardized onsite technologies containing accumulated faecal sludge. The demand for infrastructure to manage faecal sludge is increasing, however, no reliable method exists to estimate total accumulated quantities and qualities (Q&Q) This proposed approach averages out complexities to estimate conditions at a centralized to semi-centralized scale required for management and treatment technology solutions, as opposed to previous approaches evaluating what happens in individual containments. Empirical data, demographic data, and questionnaires were used in Kampala, Uganda to estimate total faecal sludge accumulation in the city, resulting in 270 L/cap·year for pit latrines and 280 L/cap·year for septic tanks. Septic tank sludge was more dilute than pit latrine sludge, however, public toilet was not a distinguishing factor. Non-household sources of sludge represent a significant fraction of the total and have different characteristics than household-level sludge. Income level, water connection, black water only, solid waste, number of users, containment volume, emptying frequency, and truck size were predictors of sludge quality. Empirical relationships such as a COD:TS of 1.09 ± 0.56 could be used for more resource efficient sampling campaigns. Based on this approach, spatially available demographic, technical and environmental (SPA-DET) data and statistical relationships between parameters could be used to predict Q&Q of faecal sludge.

1. Introduction

The current state of sanitation in urban areas of low- and middle-income countries is 2.8 billion people served by onsite sanitation, with the majority of excreta not safely managed. For example only 37% safely managed in 12 reported cities (Peal et al., 2014; WHO and UNICEF, 2017). However, the definition of onsite sanitation and faecal sludge is very broad, meaning only that it is not connected to or transported in a sewer (Strande et al., 2014). Hence, the reality is a chaotic mixture of inappropriately and haphazardly constructed containment for the onsite storage of sludge, with no level of standardization (Isunju et al., 2013). For example, a simplified classification of onsite systems in Dar es Salaam, Tanzania included pit latrines that were lined, unlined, partially lined, improved, collapsed, abandoned, tanks that were fully lined ("septic tank", "storage tank"), partially lined ("cess pit"), with no drainage, or drainage going to soakaway, open drain, overflow, water body, soakaway, or soil (Brandes et al., 2015). This status is the result of many factors, including a lack of tenure or ownership in slums, government involvement, financial resources, heterogeneous settlement patterns, and a strong focus of the Millennium Development Goals (MDGs) ending open defecation, but not developing management plans for what happens when onsite storage of sludge becomes full (Beyene et al., 2015; Günther et al., 2011; Moe and Rheingans, 2006; Oyoo et al., 2013; Tilley et al., 2014). It is commonly perceived that faecal sludge management is simpler than centralized sewer based solutions, as it involves the management of simpler technologies. Although faecal sludge management can be less expensive, it is in reality much more complicated (Dodane et al., 2012). In addition to the diversity of sludge containment types, it requires the active and complex management of personal, financial, political, legal,

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and socio-cultural interactions along the entire service chain (Chowdhry and Koné, 2012). Treatment is difficult due to wide-ranging characteristics and stabilization, which dictate selection of technical solutions, govern settling and dewatering, and influence treatment efficacy (Appiah-Effah et al., 2014; Bassan et al., 2013; Dodane et al., 2012; Gold et al., 2016; Kengne et al., 2014; Sonko et al., 2014).

Immediate solutions are needed, while in parallel developing more sustainable solutions for the future (Moe and Rheingans, 2006). This includes collection, transport and treatment of faecal sludge on a decentralized, semi-centralized, or centralized scale. Acknowledgment of the importance of faecal sludge management by governments, development agencies, municipalities, and academia is rapidly increasing, and has now been included in the Sustainable Development Goals (SDGs) (Bassan and Strande, 2011; Chowdhry and Koné, 2012; FSM Toolbox, 2017; The World Bank Group, 2016). The result is that funding is starting to become available for infrastructure. However, with the current status, reliable estimates of faecal sludge quantities and qualities (Q&Q) for the design of treatment technologies and management solutions are nearly impossible. Hence, studies are rare that quantify both Q&Qs of faecal sludge, which are necessary to estimate loadings (Fanyin-Martin et al., 2017; Ross et al., 2016). Therefore, engineers try to make reasonable estimates when designing solutions, but typically without adequate resources or time. The result is treatment plants that are immediately at capacity (e.g. Lubigi in Kampala, Uganda) (Fichtner and Associates, 2008), or way under- or over-capacity (Bassan and Strande, 2011). Inadequately sized treatment and management solutions impact operation and are a direct risk to public health.

In comparison, extensive research has gone into developing influent generator models for the design and optimization of wastewater treatment facilities, leading to quite sophisticated empirical and fundamental models. Typical model parameters include average water usage, climate data, wet and dry flows, population equivalents, soil type, length and type of sewer, and industrial inputs (Flores-Alsina et al., 2014; Martin and Vanrolleghem, 2014). Models also consider biological activity and homogenization during transport in sewer. Homogenization in sewers is significant, with even random peaks of contaminants from individual households flattened out as bell-shaped curves (Ort et al., 2005). The variation that enters treatment plants can then be modeled harmonically, with diurnal, weekly, and yearly variations (Langergraber et al., 2008).

However, this experience is not transferable to faecal sludge management, and developing solutions based solely on experience with centralized wastewater treatment in industrialized countries will result in inappropriately designed systems that are prone to failure (Bassan et al., 2015). The development of sophisticated influent wastewater models required massive operating data, with further advances limited by prohibitive resource and financial constraints of data collection (Martin and Vanrolleghem, 2014). In contrast to over 100 years of operating experience in wastewater, faecal sludge management is in its infancy, for example in the United States where 25% of sanitation is non-sewered, the USEPA only acknowledged it as a long-term solution within the last 20 years (USEPA, 2005). In addition, faecal sludge is one to two times higher in COD and TS magnitude and variability than wastewater (Gold et al., 2017). The variability is due to the differences in onsite containment technologies, retention times, household usage patterns, quality of construction, collection practices, and that it is collected batch-wise individually, and not homogenized during transport in a sewer (Strande et al., 2014; USEPA, 1984). The few attempts in the literature to model faecal sludge at scale have attempted to use numerical modeling of a mass balance approach, using data from individual pit latrines in an attempt to predict average values for a neighborhood or city (Brouckaert et al., 2013; Kimuli et al., 2016; Lugali et al., 2016; Todman et al., 2015).

Hence, there is a desperate need to develop reliable, empirical, field-based methods for the estimation of faecal sludge Q&Q at scales relevant for the design of treatment technologies and management solutions. The objective of this study was to fill that gap by developing a method of data collection and field-testing it in Kampala, Uganda. The use of statistical trends in spatially available (SPA) data based on in-field-questionnaires and demographic, environmental and technical (DET) data to measured parameters were investigated for upscaling results of data collection to regional areas.

2. Materials and methods

2.1. Overview

The method for data collection is based on the hypothesis that types of demographic, environmental and technical (DET) data that can be spatially analyzed (SPA), can be used as predictors of faecal sludge Q&Q. It is important to note these are correlations or statistical relationships, not necessarily causation, but if consistent relations are observed, they can be used as predictors. The steps taken included researching available types of SPA-DET, developing a context specific questionnaire that was used to interview customers and service providers during both emptying operations and sludge delivery, development of a sampling plan, and data analysis, as described in more detail in the following section.

2.2. Spatially analysable demographic, environmental and technical (SPA-DET) data

This research was conducted in Kampala, Uganda. Kampala has a population of 1.5 million (UBOS, 2014), which doubles during the day due to commuting populations (Kulabako et al., 2010). Of the city's residents, 92.5% are served by onsite sanitation technologies (Fichtner and Associates, 2008) and there are two existing treatment plants. Income category was the main type of SPA-DET that was obtained from the Kampala Capital City Authority (KCCA, 2012). Additional types of environmental information (e.g. groundwater, soils) were not available.

2.3. Questionnaire

The questionnaire collected information on 14 hypothesized indicators of faecal sludge Q&Q. The questionnaire included the following questions to the driver: what is the volume of your truck; who does the truck belong to; is your truck completely full (following the emptying event); was the customer's onsite faecal sludge containment fully emptied; did you add any water to the onsite faecal sludge containment; what is the source/origin of sludge (i.e. household, multiple household, institution/industry, hotel/restaurant, school, public toilet, other); and was the faecal sludge containment a lined pit latrine, or septic tank. The questionnaire included the following questions to the customers: if a household, number of inhabitants; types of wastewater entering system (i.e. toilet, bathing/washing, kitchen, other); does solid waste enter the faecal sludge containment, yes or no; if yes, what types (e.g. hygenic products, food waste, other); age of faecal sludge containment (i.e. years $0 \le 5$, $5 \le 10$, $10 \le 20$, > 20); do you have access to a water connection; volume of containment; have you ever had the faecal sludge containment emptied, when; is the containment watertight; and if septic tank, how many chambers.

2.4. Sampling plan

From December 2013 to March 2014, which includes both the dry and (short) rainy season, 180 faecal sludge samples were collected during emptying events by vacuum trucks, at the locations presented in Fig. 1. Samples were collected from a diverse range of sites representing single and multiple households, public toilets, schools, institutional/commercial/industrial, restaurants/hotels, and containment technologies (i.e. septic tanks and pit latrines). Samples were not collected from

Fig. 1. Locations for 180 samples analyzed during this study, boundary shown is Kampala city.

completely unlined pit latrines, which are rarely emptied by mechanical service providers due to inaccessibility and the risk of collapse (Nawembe et al., 2007). Sample collection included the questionnaire based interview with the vacuum truck driver and emptying customer, and following the truck to discharge locations to collect a sample. The results were cross-checked through field observations and the GPS coordinates of each emptying location were recorded. During discharge, a composite sample was taken of four samples; one at the beginning, two in the middle, and one at the end (Bassan et al., 2013). Composite samples were stored in 1 L bottles and transported on ice to the Public Health and Environmental Engineering Laboratory of Makerere University, where they were stored at 4 °C until analysis.

To estimate accumulation rate (Q_3) two emptying scenarios were evaluated; 1) containment full and fully emptied, and 2) containment full and partially emptied. Based on these scenarios, to calculate accumulation rates the volume of faecal sludge emptied by the truck was determined as representative for the volume of accumulated faecal sludge over the period since the system was previously emptied. This avoided overestimating volumes of partially emptied systems, and provided a means for validation by truck volume gauges.

2.5. Sample analysis

Sample qualities were analyzed according to standard methods with Hach Lange LCK standard tests (American Public Health Association, 1998), including analyses of physical properties for total solids (TS), total suspended solids (TSS), volatile solids (VS), and volatile suspended solids (VSS) (American Public Health Association, 1998). Chemical properties included pH, chemical oxygen demand (COD), soluble chemical oxygen demand (COD_{sol}), total nitrogen (TN), ammonia nitrogen (NH_4—N), nitrate (NO_3), total phosphorus (TP), and phosphate (PO_4—P).

2.6. Data analysis

Relations to the measured qualities with the potential indicators from the questionnaire, plus observed viscosity in the laboratory, were evaluated with R software 3.4.3 (R-Core-Team, 2017; RStudio-Team, 2016; Wickham, 2017) (n = 180 samples). Due to very high variability and uneven distribution of faecal sludge qualities, median rather than mean values were used for analyses (Schmid and Huber, 2014). In this case, using mean values would have resulted in overestimated accumulation rates that were three times higher. The confidence interval around the median (notches in the boxplots) was calculated as $\pm\ 1.58 \cdot$ IQR/sqrt (n) $\pm\ 1.58 * \frac{IQR}{\sqrt{n}}$, where IQR is the interquartile range and n is the sample size (Chambers et al., 1983). For each set of potential indicators, if confidence intervals of the median did not overlap, then they were considered to be significantly different (Chambers et al., 1983), and thus defined as a potential indicator of faecal sludge TS concentrations for this data set. These included: containment type (pit latrine or septic tank); water connection (yes or no); origin category (household, non-household, or public toilet); solid waste entering the containment (yes or no); blackwater only (yes or no); truck full (yes or no); containment fully emptied (yes or no); income category (very low, low, medium, high); containment volume (m^3 - $0 \le 5$, $5 \le 10$, $10 \le 20$, ≥ 20); containment age (years - $0 \le 5$, $5 \le 10$, $10 \le 20$, > 20); watertight containment (yes or no); number of users ($0 \le 10$, $10 \le 20$, $20 \le 40$, $40 \le 80$, $80 \le 200$, $200 \le 500$, ≥ 500); truck volume (m^3 - $1 \le 4$, $4 \le 6$, $6 \le 8$, $8 \le 10$); emptying frequency (weeks - $0 \le 2$, $2 \le 4$, $4 \le 10$, $10 \le 26$, $26 \le 52$, $52 \le 105$, ≥ 105); and during laboratory analysis, a ranking of observed consistency (low, medium, high) was recorded.

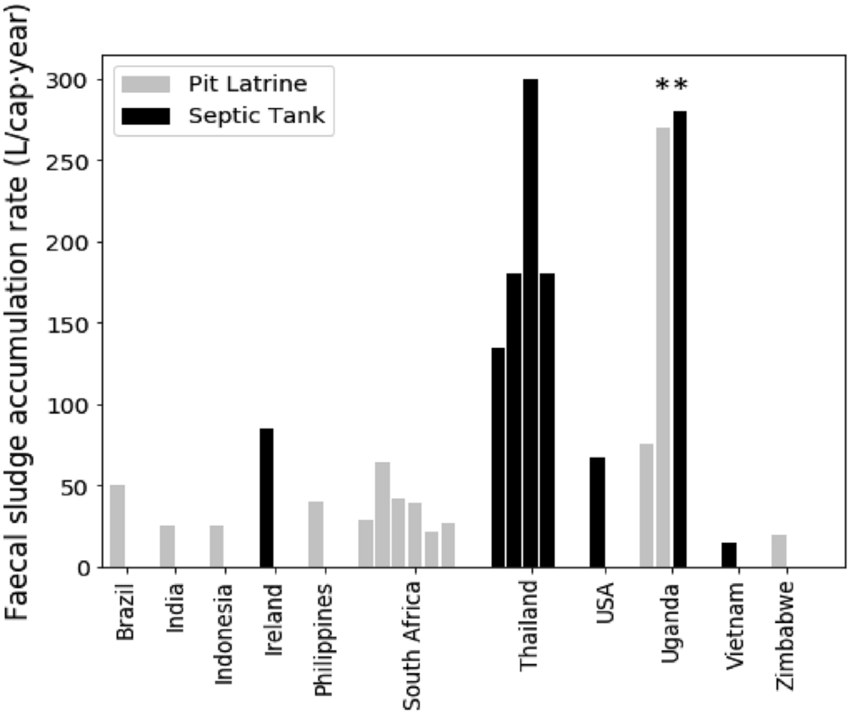

Fig. 2. Reported accumulation rates in the literature categorized by country in alphabetical order (Brazil, India (Wagner and Lanoix, 1958) Indonesia (Mills et al., 2014) Ireland (Gray, 1995) Philippines (Wagner and Lanoix, 1958) South Africa (Brouckaert et al., 2013; Still and Foxon, 2012; Still et al., 2005) Thailand (including cesspits) (Koottatep et al., 2012) Uganda (Lugali et al., 2016) USA (Howard, 2003) Vietnam (Harada et al., 2014) Zimbabwe (Morgan et al., 1982)). Bars with asterix (*) represent accumulation rates from this study.

3. Results and discussion

3.1. Quantities

Based on the fieldwork that was conducted, rates of faecal sludge accumulation (Q_3) for Kampala were estimated to be 270 L/cap·year for pit latrines and 280 L/cap·year for septic tanks. A comparison to rates reported in the literature is presented in Fig. 2. In addition, a study of Asia and Africa reported rates from 36.5 to 959 L/cap·year (Chowdhry and Koné, 2012). The wide variability of reported rates illustrates the lack of available data, with 30% of values reported in Fig. 2 coming from eThekwini in South Africa, the difficulty in determining rates based on individual systems, and transferring knowledge from one region to another due to the wide variety of influencing factors. Variability is also exacerbated by the lack of standard methods for data collection.

Most estimates for rates of accumulation have been made by observing individual systems, and then collectively applying them (stochastic), or using 60 year-old assumptions as default numbers for filling rates (Wagner and Lanoix, 1958). In contrast, this study employed a large-scale, city-wide empirical estimation approach (phenomenological) to obtain estimates that are more representative of what needs to be managed overall. Accurate fundamental models based on what is occurring at the individual household level will be difficult to achieve, based on the large number of factors that affect the sensitivity of a model, and the lack of knowledge of processes occurring within onsite systems. For example varying levels of oxygen, water content, climate, inflow and infiltration, presence of overflow pipe, user behaviors, municipal solid waste, containment design, sludge age, influent COD, hydraulic retention time, non-biodegradable fraction and soil characteristics (Brouckaert et al., 2013; Elmitwalli, 2013; Franceys et al., 1992; Gray, 1995; Howard, 2003; Koottatep et al., 2012; Lugali et al., 2016; Nakagiri et al., 2016). In addition, rates of accumulation are initially higher, and slow down after 6–12 months (Gray, 1995; Howard, 2003). Historic design filling rates based on five users and an emptying frequency of 10–15 years were intended for rural areas and will underestimate accumulation in dense urban areas (Wagner and Lanoix, 1958), for example in Kampala where there is an average of 30 users per household level latrine, and 82 people per public toilet latrine (Günther et al., 2011). Increased number of users and more frequent emptying both result in higher accumulation rates (Gray, 1995; Howard, 2003; Koottatep et al., 2012; Still and Foxon, 2012).

As illustrated by the numbers in Fig. 3, there are six stages in the faecal sludge management service chain where flows (Q = volume/time) can be quantified. To develop a truly comprehensive, long-term, city-wide management plan for faecal sludge, requires a reasonable estimate for Q_3, the total amount of faecal sludge that needs to be safely managed (latent demand), from safe onsite containment, to collection, transport, treatment, and enduse or disposal. In addition to the above complexities, due to the difficult nature of making reliable estimates, other steps in the service chain illustrated in Fig. 3 are sometimes used, however, if any of the other steps are used instead, the amount of faecal sludge would be greatly under- or over-estimated. Starting with faecal sludge that is removed from onsite containment, the six stages are

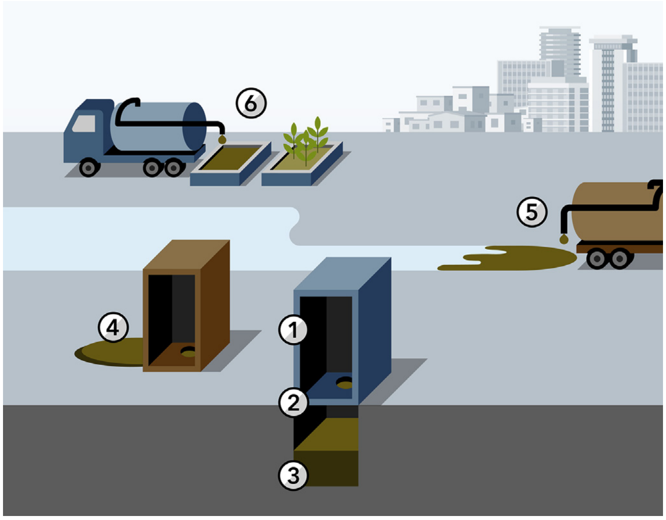

Fig. 3. Six stages in faecal sludge management service chain where different flows (Q) of faecal sludge can be quantified.

Table 1
Summary of faecal sludge quantification in Kampala at the six different stages for quantification in the faecal sludge management chain as illustrated in Fig. 3.

Faecal Sludge Quantification	Per Capita [L/cap·year]
Q_1 Excreta Produced	600[a]
Q_2 FS produced	24,840[a]
Q_3 FS accumulation (based on median)	
Pit Latrines	270[b]
Septic Tanks	280[b]
Q_4 FS emptied, not collected	12[c]
Q_5 FS collected, not delivered	0[c]
Q_6 FS collected, delivered to treatment	124[c]

Estimates based on literature:
[a] (Rose et al., 2015; Schoebitz et al., 2016).
[b] This study.
[c] (Schoebitz et al., 2016).

faecal sludge that is collected and delivered to treatment (Q_6), faecal sludge that is collected and dumped in the environment (Q_5), and faecal sludge that is emptied directly into the environment without collection (Q_4). Starting from the generation of faecal sludge, are total excreta produced (Q_1), faecal sludge production (Q_2), and faecal sludge accumulation (Q_3). To illustrate the importance of Q_3, estimates for all six steps are presented in Table 1 (assumptions and calculations are based on literature and explained in detail in the Supplemental Information). By knowing Q_3, management solutions can be developed that include appropriate treatment plant capacities and emptying programs, and allows for a step-wise approach to designing management that includes designing for the existing situation, while simultaneously planning for the future. Q_3 will also include the amount of faecal sludge that is safely contained onsite, for example, currently in Kampala, 24% of accumulated faecal sludge is considered safely contained (Schoebitz et al., 2016). Management decisions could include designing for longer emptying frequencies, preferably more than a year to decrease volume and increase sludge stability (Elmitwalli, 2013). As collection and transport solutions are implemented, the demand for treatment will logically also increase. Faecal sludge management is also complicated by the fact that upgrading citywide sanitation will also change rates of total accumulation. Other complexities will always include how to accurately predict commuting populations, population growth, impact of border regions on infrastructure (e.g. trucks bringing sludge in from outside the city boundaries), and lack of available and reliable data.

To understand the complexity of making estimates for Q_3 for septic tanks and pit latrines, a more detailed breakdown by emptying frequency and usage is provided in Fig. 4. This variability complicates regional estimates required for management purposes, but if the patterns are recognized, and relationships among predictors are identified, this could be used to make much more accurate estimations. For example, non-household septic tanks (i.e. public toilets, schools, institutional/commercial/industrial, and restaurants/hotels), which were also frequently emptied (i.e. defined as < 1 year, but which included emptying as frequently as once daily), had higher accumulation rates than households. This was also observed in Thailand, with accumulation rates of 300 L/cap·year for cesspits that were emptied once a month to once a year (Koottatep et al., 2012). In this study, non-household onsite containments tended to have higher numbers of users than household level systems. Studies in South Africa observed a decrease in accumulation rate with increased number of users, however, this was with longer emptying frequencies (< 5 years), for households in peri-urban to rural areas (Buckley et al., 2008; Foxon et al., 2011; Still et al., 2005). In Kampala, many of the non-household containment systems were sealed without overflows, which has also previously been observed in Thailand to increase rates of accumulation (Koottatep et al., 2012). Frequently emptied sludge does not have time to degrade, and hence rates of accumulation (Q_3) are closer to faecal sludge production (Q_2). More resource efficient solutions should provide time for contained faecal sludge to degrade and reduce in volume (Still and Foxon, 2012), and/or include onsite dewatering, which could then be more readily collected and transported to treatment.

Another important aspect to note with the large differences based on usage patterns, is that non-household sources of sludge have not previously been differentiated in the literature. However, this represents a significant source of faecal sludge in urban areas, for example up to 50% of the incoming faecal sludge at the Lubigi treatment plant in Kampala is from non-household sources (Schoebitz et al., 2016). Due to the high volume of people commuting daily into urban areas in low-income countries (e.g. 2 times daily increase in population in Kampala), use of non-household toilets is equally important to consider in determining Q&Q of faecal sludge.

3.2. Qualities

3.2.1. Total solids

For sustainable management practices, qualities must be considered simultaneously with quantities (loadings). This approach was designed to capture information that could be up-scaled for both at the same time. In this study, TS was selected for initial evaluations, as it is the most commonly used design parameter for established faecal sludge

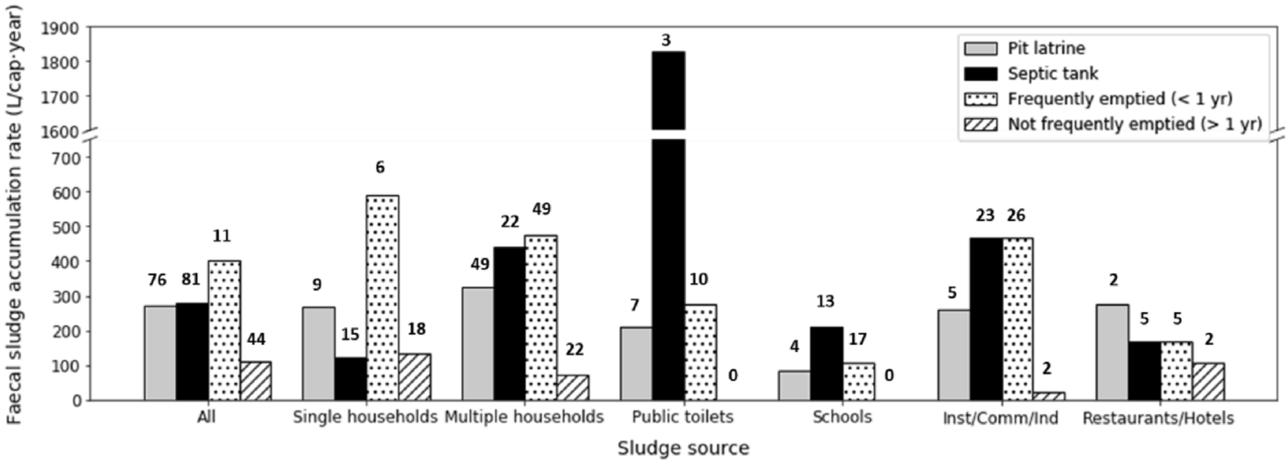

Fig. 4. Comparison of faecal sludge accumulation rates in this study for single and multiple households, public toilets, schools, institutional/commercial/industrial, and restaurants/hotels Accumulation rates are median values, and presented by type of system (pit latrine or septic tank) and emptying frequency. Numbers above bars are samples used for calculation.

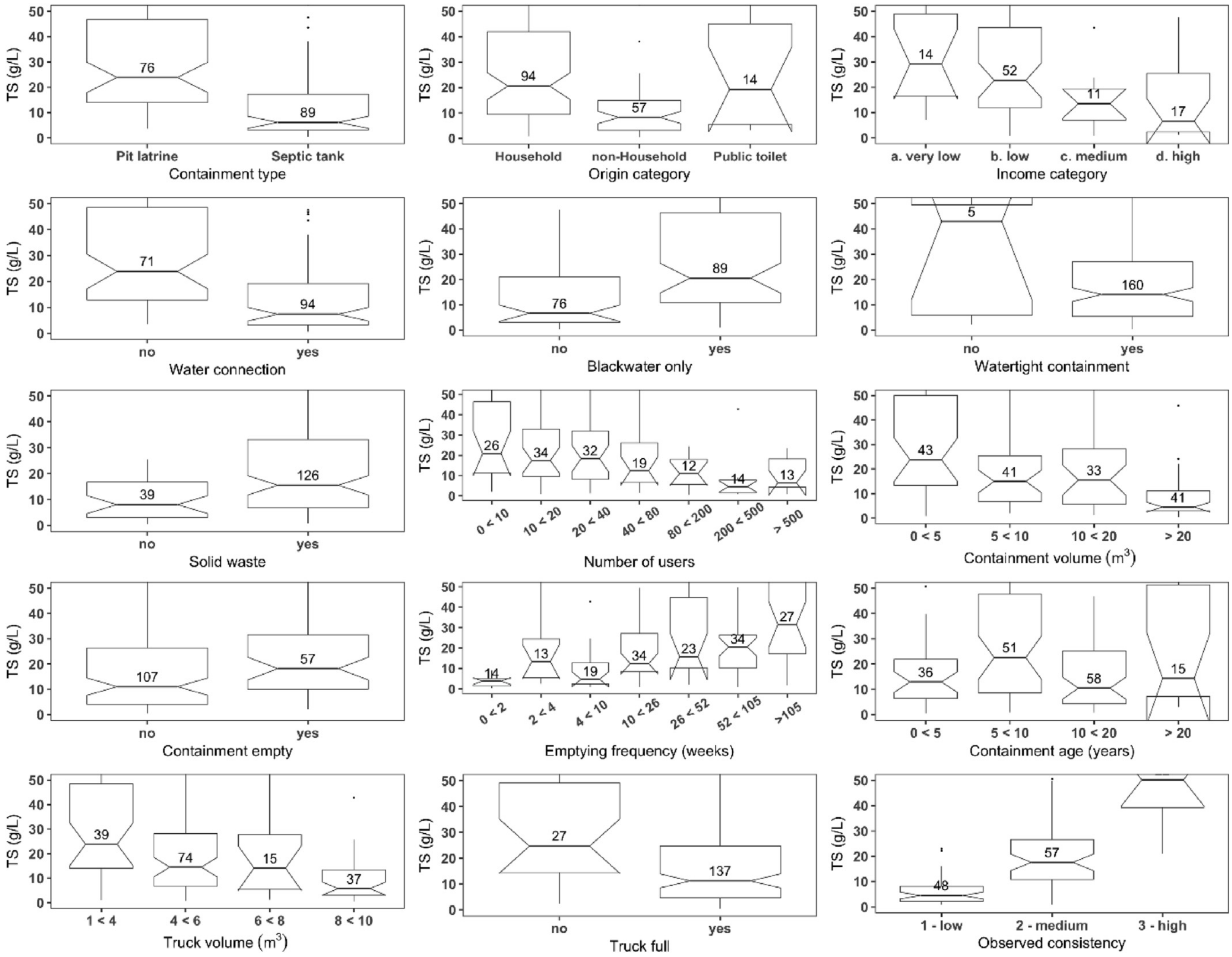

Fig. 5. TS concentrations for 14 possible indicators and observed consistency of sample in the laboratory. n on box plot represents number of samples for respective indicator, notches in boxplots show confidence interval around the median.

treatment technologies such as drying beds (Strande et al., 2014). Quantified TS concentrations are presented in Fig. 5. Septic tank sludge was more dilute than pit latrine sludge, which fits with other observations that septic tank sludge has a higher water content than pit latrine sludge (Bassan et al., 2013; Nzouebet et al., 2015), due to a higher prevalence of flush toilets. However, TS concentrations of public toilet sludge were not significantly different from household or non-household sources. Whereas conventional knowledge has been that public toilets have unique sludge qualities based on usage and emptying patterns, it appears type of containment is more relevant (Appiah-Effah et al., 2014; Heinss et al., 1998; Strauss et al., 1997). This is an important distinction, as in urban areas of many low-income countries, sludge from public toilets can represent a significant volume of the total sludge produced in a city (Günther et al., 2012).

The trends illustrated in Fig. 5 could be used to make estimates for a city based on SPA-DET-based data. TS concentrations were significantly different based on level of income. This trend could be due to septic tanks being located in higher-income areas with more access to household water, and pit latrines in poorer areas with less dilution from grey water (Berendes et al., 2017). Researchers in Brazil also identified differences in patterns of wastewater generation based on income level (Campos and Von Sperling, 1996). TS concentrations were also significantly lower if households had a water connection, and/or if the containment captured black water only. However, they were not different based on whether or not the containment was reported to be watertight, potentially because actual underground conditions are difficult to discern. If users answered that they did not put solid waste into their containment systems the sludge was less concentrated. This is consistent with other observations, as containment with flush toilets tends to have less solid waste due to the difficulty of passing it through the plumbing (Byrne et al., 2017). The following indicators were also predictors of non-household sources, and less concentrated sludge; higher number of users, larger containment volumes, more frequently emptied, larger trucks, and if the trucks were full at the time of emptying.

When the containment was reported to be fully emptied, it was related to more concentrated sludge, which is in contradiction to the other trends. This could be due to the bottom layer of pit latrines being densely compacted sludge that is too thick to be removed by conventional vacuum trucks (Brandberg, 2012; Radford and Fenner, 2013). TS concentrations based on what users answered for containment age were also not different. The fundamental reasons for all of the above correlations are not fully understood, however, consistent correlations like this could make it possible to use SPA-DET data as predictors to develop sampling plans to estimate qualities of faecal sludge, at a scale relevant for the design of management and treatment solutions.

Due to the high variability of faecal sludge, the current status of onsite sanitation technologies, and the informal nature of sanitation provision in low-income countries, implementing a laboratory based sampling plan to determine reliable characteristics of faecal sludge would be prohibitively resource and time intensive. However, combining a laboratory-based sampling plan together with SPA-DET data and questionnaires, could greatly increase the reliability of a study, while simultaneously reducing costs. When evaluating predictors of faecal sludge qualities, it would also be valuable to include SPA-DET data on physical factors such as ground water, soil type, and elevation. Unfortunately, in low-income countries readily available SPA-DET data is in general lacking (e.g. was not available in Kampala) and illustrates another need to develop methods based on data that is readily available. The laboratory technician's observation of whether sludge had low, medium or high consistency also appeared to be a good predictor for range of TS concentrations. This is consistent with reported positive correlations between shear strength and TS observed for pit latrine sludge (Bosch and Schertenleib, 1985; Radford and Fenner, 2013). With experienced field technicians, visual appearance such as color and thickness could also provide a way to improve predictions of characteristics.

3.2.2. COD to TS ratio

In addition to TS, metrics of oxygen demand are also important design parameters. As illustrated in Fig. 6, the COD and TS of samples in this study had a strong correlation. The average COD:TS ratio for all faecal sludge characterized in this study was 1.09 ± 0.56, or 0.84–1.25 from the 1st to 3rd quartile, in comparison to a typical range of 0.60–0.65 for wastewater influent (Tchobanoglous et al., 2003). Based on the variability of faecal sludge characteristics, it is difficult to draw conclusions about the relative stability of faecal sludge in comparison with wastewater influent. However, values for faecal sludge and wastewater influent both fall within the range of reported COD:TS ratios for faeces (0.57–1.70) (Rose et al., 2015). Many wastewater models are based on empirical evidence and established correlations, this suggests it could also be achieved with faecal sludge. A correlation could also be used to reduce the required number of samples and analytical costs, for example conducting an extensive sampling campaign with questionnaires and TS analysis, with in laboratory validation of COD for a fraction of the samples. Platforms such as BORDAs sanitation tool for Dar es Salaam, Tanzania, could present a way for stakeholders to share data across projects, and buildup models to utilize predictors and correlations, increasing resource efficiency (Bright-Davies et al., 2016).

3.2.3. All parameters

In addition to TS and COD, samples were analyzed for a full suite of solids, organics and nutrients. The results are summarized in Fig. 7 by household, non-household, or public toilet, together with pit latrine or septic tank. The data presented in this manner is not significant, however, it illustrates interesting trends that would be significant with a larger data set. Septic tank sludge characteristics are in line with previously reported values (e.g. TS 11.9–72.0 g/L; VS 7.1–33.8 g/L; COD 7.8–43 g/L; pH 6.9–7.9; NH_4—N 0.18–0.6 g/L (Gold et al., 2017; Heinss et al., 1999; Koottatep et al., 2001; Semiyaga et al., 2017)). TS and COD of sludge from lined and partially-lined pits was on the low end of the range previously reported for lined pits in Kampala (e.g. TS 51.4 ± 29.2 g/L; COD 65.5 ± 44.0 g/L (Semiyaga et al., 2017)). However, that was collected directly from pit latrines, whereas in this study, sludge was collected from the discharge of vacuum trucks. As also noted above, public toilets in Fig. 7 do not represent a reliable predictor of faecal sludge characteristics, and non-household faecal sludge is less concentrated and lower in strength compared to household and public toilet sludge.

4. Conclusions

The strength of this approach, is the wide variability of sludge sources used to represent faecal sludge on a city-wide scale. This approach will not accurately predict what is happening at a fundamental level in each individual onsite containment, but instead averages out complexities to predict what needs to be managed on a centralized to semi-centralized scale. This approach is powerful for the design of management solutions and treatment plants, as it represents what will actually arrive at treatment plants. This is analogous to modeling what is transported in a sewer, versus trying to capture what is happening at each individual household. Data could be used as presented here to indicate trends in Q&Q that can be used for city-wide estimations. In addition, as we build up databases of empirical data, we can start to evaluate how it fits models, and as models are developed, they can be calibrated with experimental data, including correlations of quantities, qualities (organic and solids fractions) and observational facts (SPA-DET data, types of system, emptying).

Modeling based on the fundamentals of what is occurring at the micro-scale will probably never be feasible to apply on a city-wide scale due to the complexity of influencing factors and the lack of homogenization. However, as these individual models become more refined, they can be aggregated into a larger-scale approach like this, and are useful to understand what is happening at the micro-scale. Based on the observed differences in this study, it illustrates the necessity of evaluating neighborhoods or clusters of development where there are similarly used systems as a component of city-wide sanitation planning. As more information is available at this level, for example individual

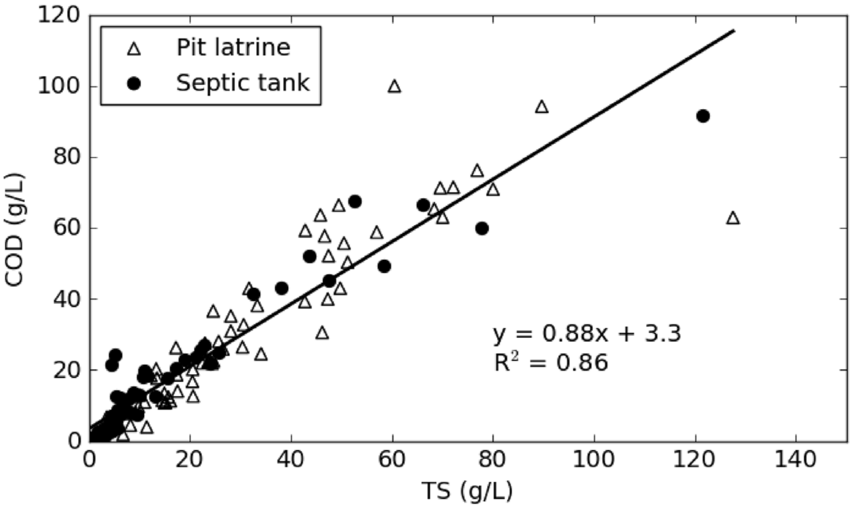

Fig. 6. Correlation of COD and TS for the faecal sludge evaluated in this study.

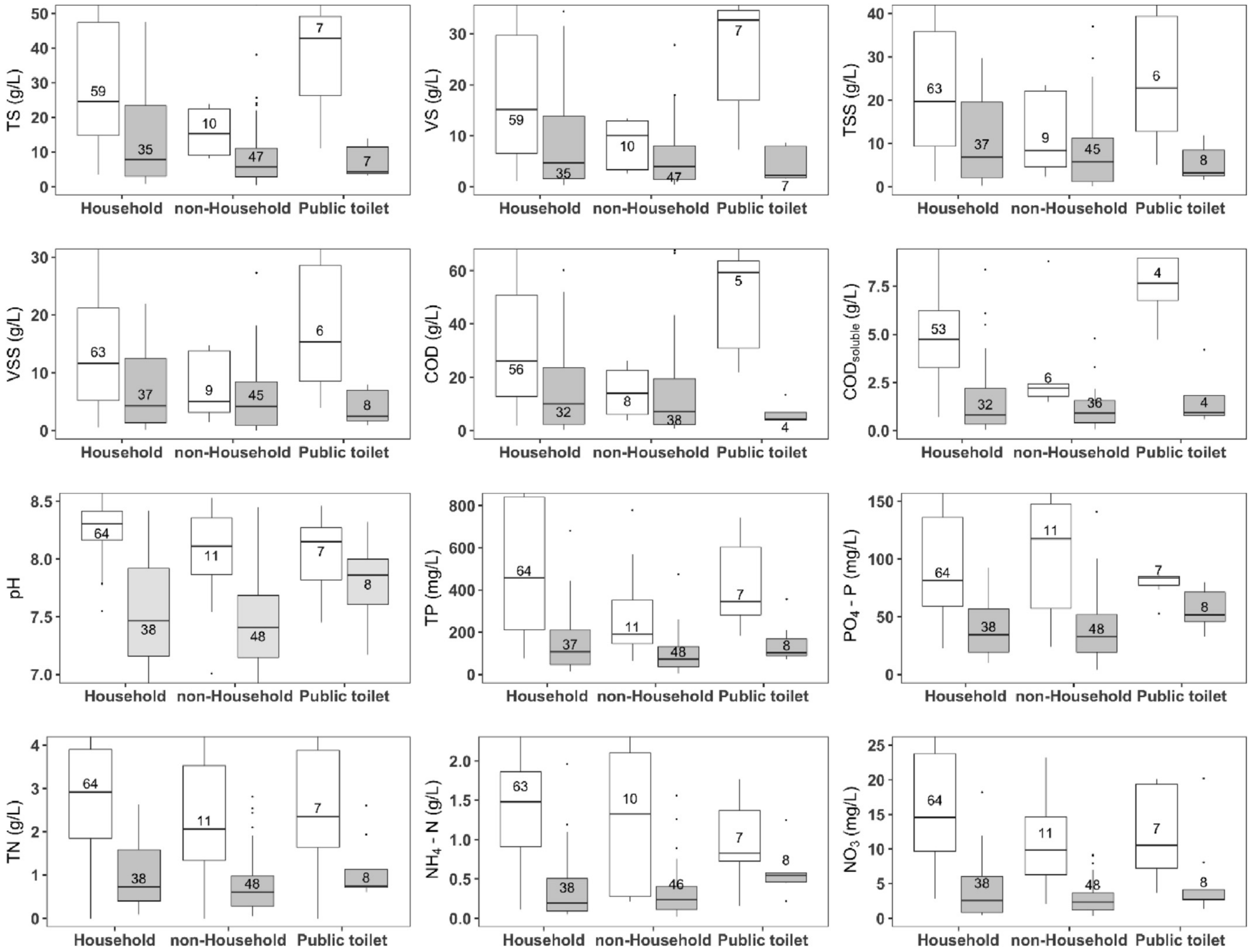

Fig. 7. Containment type and origin category for all analyzed parameters. White bars are pit latrines, grey septic tanks. Number on bars is samples used for calculation, with median value shown on box.

models of pit latrines at schools, or partially lined pit latrines in informal developments, or septic tanks at factories, they can also be incorporated to improve the accuracy of the overall larger scale model.

A similar approach could be applied in any city to further understand and evaluate the needs for faecal sludge management. In Kampala there are existing faecal sludge treatment plants and legal discharge locations, which facilitated data collection. However, the same approach could be taken with any type of emptying practices, and regardless of existing treatment plants. The importance of faecal sludge management is increasingly being acknowledged, but based on the misconception that individual low-tech onsite technologies are simpler to manage than centralized sewer-based systems, adequate funding is not being allocated. As governments, municipalities, and development agencies start to develop infrastructure for the management of faecal sludge, it is necessary that they also allocate adequate resources for appropriate planning, including reliable estimates of the total quantities and associated qualities of faecal sludge for each specific location. Without logical designs, sanitation solutions will continue to fail in low-income countries.

In summary, the key conclusions of this study are:

- previous attempts at estimating neighborhood or city-wide Q&Q of faecal sludge based on individual pit latrines are not accurate due to the high-variability of faecal sludge at the individual containment level;
- the wide range of accumulated faecal sludge calls for context-specific estimates rather than universal default numbers for filling rates;
- the approach to SPA-DET data collection presented here can provide more accurate predictions with an aggregated average that incorporates complexities of varying Q&Q;
- statistical relationships among characteristics of faecal sludge can be used to reduce overall sampling time and costs (e.g. COD:TS);
- prior to developing plans for management of faecal sludge, and infrastructure for treatment, adequate resources need to be allocated to develop reliable estimates for Q&Q of the total amount of faecal sludge that accumulates;
- additional research is needed to determine how models based on data collected in this fashion could be applicable across multiple cities or regions.

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Strande conceived of the presented idea, developed the theory, supervised the project, and took the lead in writing the manuscript. Lars Schoebitz analyzed data, contributed to theory and writing, and supervised implementation. Fabian Bischoff was responsible for carrying out all fieldwork and laboratory analyses. Daniel Ddiba and Francis Okello contributed to fieldwork and laboratory analyses. Miriam Englund and Barbara J. Ward contributed to data analysis and writing. Charles B. Niwagaba supervised fieldwork and laboratory analysis.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.06.100.

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