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Modeling sludge accumulation rates in lined pit latrines in slum areas of Kampala City, Uganda

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Disposal of faecal sludge particularly in slum areas is a difficult undertaking given the lack of space and resources. Inaccurate prediction of sludge accumulation rates (SAR) in pit latrines leads to unplanned pit latrine emptying. Given that the users and owners cannot afford the conventional emptying techniques frequently, inappropriate methods such as open defecation and emptying into storm drainages are employed which consequently contribute to environmental and health-related challenges. The main objective of this study was to develop a predictive model for sludge accumulation rates in lined pit latrines in slum areas of Kampala so as to guide routine management of pit latrines. This mathematical model was developed using a mass balance approach with a sample space of 55 lined pits. The developed model gave an average sludge accumulation rate of 81±25 litres/person/year with an efficiency of 0.52 and adjusted R^2 value of 0.50. The model was found to be sufficient and most suited for rental and public pit latrines given their bigger percentage in the slums. Further studies should include geo-physical characterization of soil and drainage of pit latrine sites so as to improve model accuracy.

Key words: Faecal, sludge accumulation rates, slum areas, lined pit latrines.

INTRODUCTION

Like many developing countries, the rural-urban migration has constrained local council authorities in Kampala City of Uganda to a level that they cannot cope with service delivery. The lack of proper urban housing has forced millions into informal settlements such as slums, where basic services including sanitation and hygiene are appalling. Slums are mainly located in areas of high ground water table (Fogg, 2008; Katukiza et al., 2014) that necessitate frequent pit emptying. The common emptying methods include use of vacuum tankers, manual emptying and the newer use of gulpers and nibblers. Most of the informal settlements are temporary

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and illegal (UN-HABITAT, 2007; Ministry of Lands, Housing & Urban Development (MLHUD), 2008) and based on the sanitation policy, on-site sanitation is the responsibility of the user (Kariuki et al., 2003). The business of pit emptying is mainly carried out by private pit emptiers using vacuum tankers. Emptying charges are mainly based on distance and the capacity of the truck. The charges also depend on the pit latrine characteristics such as depth and accessibility, faecal sludge characteristics, disposal site and geography of the site (Thye et al., 2011; Murungi and Van Dijk, 2014; Mikhael et al., 2014). As a result, pit emptiers charge a fee that ranges from 25 to 50 US dollars for a trip within a distance of 5 km. In cases where there is need to remove non faecal matter such as polythene bags, sanitary towels, clothes and in congested areas requiring disposal trips within a distance of 5 km where there is need for an extra vacuum pipe to be added, the price goes up by 3 to 10 US dollars (Murungi and Van Dijk, 2014).

Most of the residents in slum areas are low-income earners (Morella et al., 2008) thus, the cost of conventional pit emptying is high. It requires pit owners to actively save and plan for pit emptying. For pit latrines that cannot be emptied by tankers due to poor accessibility and cost, manual emptying is carried out (Kone and Chowdhry, 2012; WUP, 2003). This involves accessing the pit by inserting a hole on the side, and removing the sludge usually with simple tools such as spades, shovels and buckets (WSP, 2014; Eales, 2005). This practice is risky due to the pathogenic content of the sludge with the presence of dangerous micro-organisms such as Ascaris, *Salmonella species* (Parkinson and Quader, 2008; Murungi and Van Dijk, 2014). Besides, sludge is often dumped into the environment (Klingel et al., 2002) by simply disposing it off in the nearest streams and drainage channels (Schaub-Jones et al., 2006; Samuel, 2008). Given that the pit latrines are located in high water table areas, they are usually shallow. The pit latrines were not meant for solid waste disposal but given the poor management practices in the slum areas (Musiige, 2010) they fill up when the owners and users are not well-prepared for their emptying (Still et al., 2013). Desperate times call for desperate measures and so the pit latrines are either used when full or pit users seek alternative methods such as use of plastic bags and emptying into streams during the rainy season leading to a deplorable sanitation in the areas (Kulabako et al., 2007; Kimuli et al., 2016). This affects the environment and health of the residents in these areas with frequent opportunistic disease (e.g. cholera and typhoid) outbreaks among the slum dwellers in Kampala (Kulabako et al., 2010). In addition, the pit latrines in the slum areas are few compared to the population, so it is not an unusual sight to have a pit latrine with many users (Isunju et al., 2013) and there is always vandalism of the locks on the pit latrines and so the number of people using the pit latrines is usually higher than that reported (personal observation in the field data collection).

The responsibility of pit emptying and maintenance is still carried out by the pit owners or landlords for the case of rentals. Given that most of the landlords do not stay near their tenants or the pit latrine, pit latrines are usually emptied past the time they are full. There has been attempts by earlier researchers (Runyoro, 1981; Brouckaert et al., 2013) to address the issue of inaccurate prediction of sludge fill-up rates but this information was generalized for a wide range of pit latrines and it was not very applicable to the slum areas and it was necessary to determine the pit filling rates specifically for these areas (Bakare, 2014). It is against this background that the overarching objective of this study is to develop a predictive mathematical model capable of simulating sludge accumulation rates in lined pit latrines in the slum areas, and this model can be used to develop an algorithmic tool that would aid in the planning for emptying of the pit latrines.

MATERIALS AND METHODS

Study area

This study was carried out in the slum areas of Kamwokya, Luzira, Bwaise, Ndeeba, Banda, Nakulabye, Naguru, Kibuye and Kabalagala, all located within the five divisions of Kampala city (Figure 1). A total of fifty five pit latrines were studied from August, 2014 to July, 2015 and these were purposively chosen basing on the pit history available and willingness of the owner/ user to engage with the team carrying out the study. Pit latrines in the slum areas of Kampala city have unique characteristics unlike those study observed elsewhere in Africa (Bakare, 2014; Still and Foxon, 2012; Buckley, 2008). The majority of slum areas in Kampala are located in low lying areas (altitudes between 650-850 m above sea level) with high water tables. This means that the majority of pit latrines are shallow (not more than eight feet in depth). There is also frequent flooding especially during the rainy season and this is the reason the practice of emptying into streams is very common (Kulabako et al., 2007). The slum areas are unplanned informal settlements and with the exception of the public pit latrines that are built by the city authorities, the other pits are built with different construction designs and styles. The pits have very many users and most of them take on the solid waste disposal role as well (Isunju et al., 2013; MLHUD, 2008).

The pit latrines in the slum areas were classified into lined and unlined. Majority of the pit latrines were lined although areas such as Ndeeba, Luzira and Nakulabye that were not originally slum areas had most of the pit latrines as unlined. This study specifically focused on the lined pit latrines and these were divided into public pit latrines (more than 82 users); rental pit latrines (single pit used by several households but limited to only those households) and private pit latrines (used by single household).

Field data collection

Pit sampling

The type of material deposited in the pit was assessed basing on

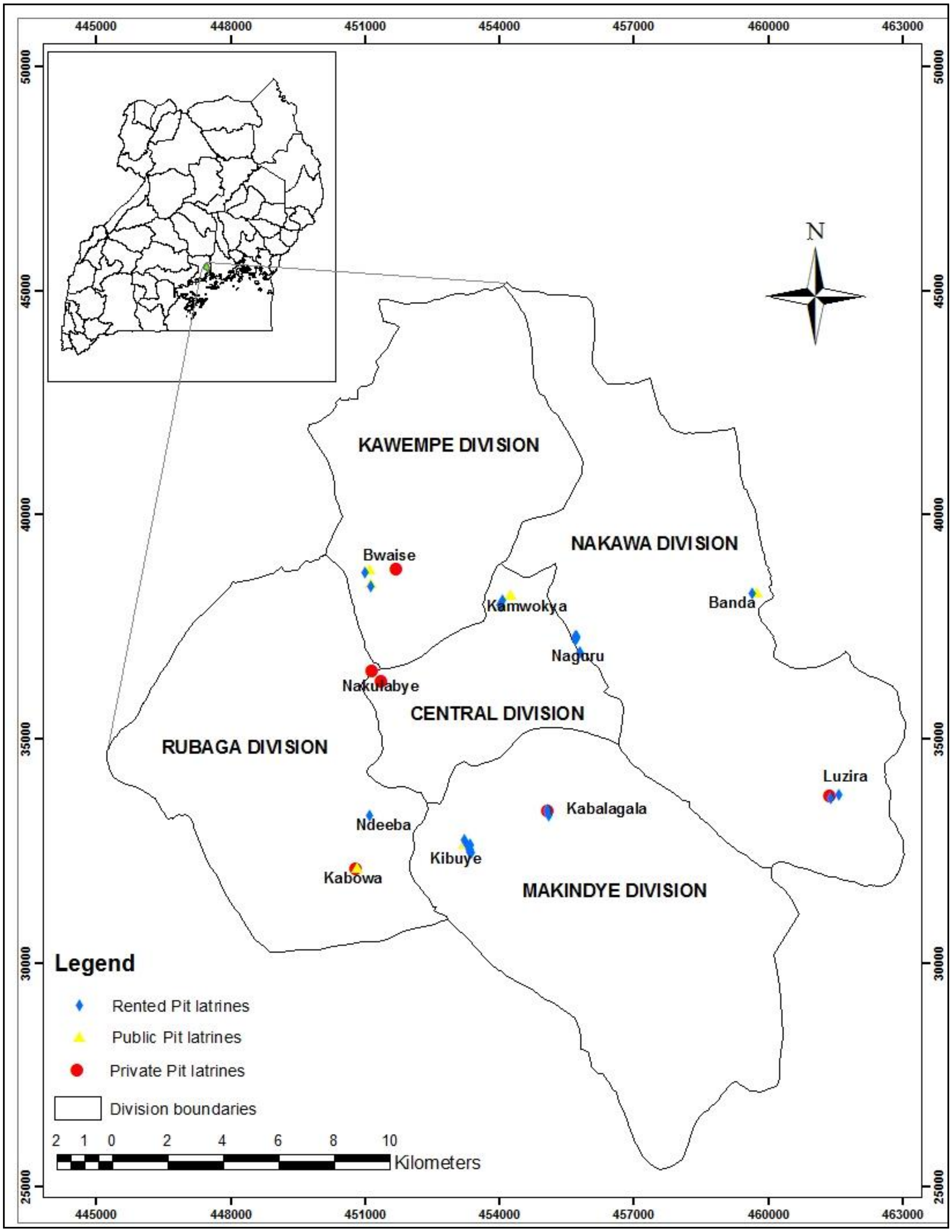

Figure 1. Map of Kampala showing selected pit latrines.

observation of the pit latrine contents in the pit and as the pit latrines were being emptied. Samples were collected using the pit sludge sampler (Figure 2). This tool was developed specifically for sampling faecal sludge. It was lowered into the pit latrine, adjusted by pushing the inner handle to ensure that the bottom can is open. The piston was then pulled to suck a reasonable quantity of sample. The sampling tool was removed from the pit latrine and the contents emptied into a sample container that was clearly marked

Figure 2. Sampling of faecal sludge: Pit sludge sampler (Left)-; Pit sludge sampler in action (Right).

Figure 3. Depth tool with sludge markings.

with the sample location, date and description of the pit latrine.

Pit size and depth measurements

The size of the pit latrine was measured with a tape measure for the length and width. The sludge depth was measured using a sludge depth measuring tool that was purposely developed for monitoring sludge depth changes (Figure 3). The tool was dipped into the pit latrine and the top layer of the sludge registered a mark on the tool which had a metric ruler attached to it. This reading gave the depth of sludge in the pit latrine.

Rate of degradation test

The rate of degradation on faecal samples measured the long term effect of aerobic and anaerobic degradation. The rate of degradation was measured in an experiment that was set up to measure mass loss rates at different moisture content levels; that is 80-90% and 90-100% (Buckley et al., 2008) which were the moisture content ranges found in the sampled pit latrines. Six samples were randomly selected for this experiment because of the time duration of the test (three months) and space requirements for the set-up. A small quantity (15 grams) of each of the selected samples was placed in sealed containers at each of the moisture levels and each sample was replicated three times. A control with only water was also set up to cater for the loss due to evaporation. The test was set up for three months with mass loss measurements taken weekly to determine the average mass loss over a predetermined period of time. After the three months, the percentage mass loss was computed and used to estimate the rate of degradation in the pit latrines. The rate of degradation was determined using the first-order kinetic equations:

$$dM / dt = -kt$$

With separation and integrating;

$$M_2 = M_1 e^{-kt} \qquad (1)$$

Where M_1 is initial mass at start of experiment; M_2 is mass after time, t= three months. Given that all these values are known, k, first order reaction rate constant can be calculated.

Modelling sludge accumulation rates

Model selection

Earlier model approaches to sludge accumulation rates considered the amount of faecal matter that would go into a pit latrine and accumulated over a period of time as contributed to by the number of users (Runyoro, 1981; Wagner and Lanoix, 1958). For situations where this data was not available, sludge accumulation rates were assumed based on relative location to ground water and type of

Table 1. Model parameter

Parameter	Value and its unit	Source
Faecal excretion rate	260g/person/day	Niwagaba (2009)
Fractional content of non-faecal matter	25.8%	Zziwa et al. (2016)
Density of faecal excreta	1000g/l	Murphy, 2015
Yield of un-biodegradable material from degradation of biodegradable material, z	0.1 m^3/m^3	Brouckaert et al., (2013)
First-order kinetic constant, k	0.002	Rate of degradation test and comparable with Brouckaert *et al*, 2013

anal cleansing material used (Franceys et al., 1992; Mihelcic et al., 2009). This had some shortcomings for areas where this data was not available or easily accessible and hence, a new model approach was developed that considered the inflow of faecal matter into the pit latrine, the degradation process that takes place and the new solid material formed plus the outflow. In addition, non-biodegradable material that is thrown into the pit latrines was later included in the inflow (Still and Foxon, 2012; Bakare, 2014; Murphy, 2015). This more comprehensive modeling approach was adapted and modified for this study. As a consequence, lined pit latrines were considered only to have input of faecal matter in the pit latrine; degradation of the faecal matter and addition of new material from the degradation process. This was assumed so because lined pit latrines are closed up to the environment so there is negligible outflow or inflow of any material through the pit surface apart from through the pit drop hole. Thus, given the nature of the lined pit latrines in Kampala slums, a simple mass balance was considered for sludge accumulation as shown in Equation (2).

$$Inflow - Reaction - Outflow = Accumulation \tag{2}$$

The inflow included; urine, faeces, anal cleansing materials, detergents, rubbish and water used for cleaning; the reaction conversion was considered to be due to anaerobic processes though some aerobic processes could take place especially at the top of the pit latrine and the outflow included drainage from the pit and evaporation to the atmosphere (WINSA and WRC, 2011).

Model development

Model development included using a set of equations that took into account the input of faecal matter in the pit latrines, the degradation and finally the accumulation in the pit latrine. The rate at which a pit fills depends on the rate of addition of material in the pit and the rate of degradation. The process of model development followed the series of equations 3 to 6.

$$Faecal\ \ Inflow = N \times v \tag{3}$$

Where:
N is the number of users and v is the average volume of faecal excreta per person per year.
For a first-order reaction, the volume of initial faecal sludge reacting depends on the reaction rate and is expressed in the form of differential equation, that is

$$-r = dV/dt = kV$$

Which separating and integrating will give;

$$V = V_o e^{-kt} \tag{4}$$

Where:
r is the reaction rate, and k is the first order reaction rate constant; V_o is the initial volume of faecal sludge in the pit latrine; V is the volume of sludge in pit after degradation during time, t. For every 1 m^3 of biodegradable material, z m^3 of unbiodegradable residue is formed and this also contributes to the final volume of sludge in the pit latrine after an accumulated time as given in equation (5). The mass balance equation;

$$V_R = V + z(V_o - V) + V_n \tag{5}$$

Where: V_R is the total volume accumulated in a pit after time, t in years; z is the fraction of un-biodegradable residue; and V_n is the volume of non-degradable products in the pit latrine in litres. Sludge accumulation rates are in units of litres per person per year and so the volume of accumulated sludge in the pit latrine is converted into this format.

$$SAR = \frac{V_R}{n \times t} \tag{6}$$

Where:
n is the number of users for a particular pit latrine.

Table 1 is a summary of the model parameters as adopted from various researchers. The percentage of non-faecal matter, in the pit latrines was adopted from Zziwa et al. (2016). The faecal excretion (Table 1) rate used was based on the assumption of one stool per person per day on average. This was a realistic assumption in the slum areas as most adults were at work most of the day and used the pit latrines either in the morning or at night after work.

Model calibration

Model calibration was carried out using fifteen (15) pit latrines (27% of the total pit latrines) that were selected from the same slum and whose sludge accumulation rates were calculated using equations 4 and 5. The pit latrines were randomly chosen from the same slum to ensure that there was no variability caused by geo-physical factors and soil characteristics in the collected data. In the first phase, the sludge depth in the pit latrine was measured. In the subsequent phases, the sludge depth was measured and the change in the depth was used to calculate the sludge accumulation rate after a pre-defined period of time of five months followed by measurements after one month. The model was calibrated by correcting the model results with an addition factor that varied depending on the pit latrine and its calculated sludge accumulation rate (a form of correction factor) to ensure that they were similar to the field results.

Model validation

While the performance of the identified models is promising, the overall quality of the models had to be assessed by validation on separate data sets; thirty five (35) pit latrines from different slum areas in Kampala. The software used to run the model validation was GenStat discovery edition 4 and Microsoft excel 2010 to carry out the paired t-tests to determine a significant difference in the predicted and observed values.

Optimization criteria

In order to select the correct model structure, it was important to have a performance measure which captures the essential features of the model, so that the question of how good a model really is can be answered in a satisfying way. After all, the first and most straightforward test of appropriateness for any model is its ability to reproduce observed dynamics given relevant inputs. The criterion to be maximized in this paper was the R^2 value from regression model, which is often expressed in percentage form (Neter et al., 1990). The values obtained from the criterion reflect the percentage of output variation explained by the model (i.e., $y_h(t)$). Moreover, the R^2 as given by equation (7) does not address the tradeoff between the model accuracy and number of parameters.

$$R^2 = 100\left(1 - \frac{\sum_{t=1}^{N}(y(t) - y_h(t))^2}{\sum_{t=1}^{N}(y(t) - mean(y(t)))^2}\right) \tag{7}$$

With y (t) the measured output at discrete time t and y_h (t) the model output at discrete time t, the performance index was used to evaluate the adequacy of the model.

It should be noted that R^2 with value 100% means a perfect fit between model and data over the entire data set; that is., y_h (t) equal to mean (y (t)) over the entire interval which is not satisfactory at all for the highly dynamic system in this study; R^2 with value 0% means that the model explains none of the variability of the response around its mean and R^2 with negative value means that the model predictions are even worse than the mean value. Another criterion used in this paper to assess the performance of the identified model was the Nash Sutcliffe value. The approach followed by Nash and Sutcliffe (1970) was to build a relative index of agreement or disagreement between the observed and computed values of the model and this can be used to compare model performance between periods. It basically measures the improvement made by the model in predicting sludge accumulation rates in comparison to the average value of the observed values. It starts from the sum of square errors given by equation 8;

$$F_o = \sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2 \tag{8}$$

Where *F* is the index of disagreement, $Q_{obs,i}$ and $Q_{sim,i}$ are the observed and predicted values at time step i, the sum being taken over n times steps of a pre-selected period. F is analogous to the residual variance of a regression analysis. The initial variance F_o is given by equation 9:

$$F_o = \sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2 \tag{9}$$

Where $\overline{Q_{obs}}$ is the mean of the observed values over the pre-selected period. Nash and Sutcliffe (1970) defined the efficiency of the model E as the proportion of the initial variance accounted for by the model as given by equation 10:

$$NS = 1 - \frac{F}{F_o} \tag{10}$$

The range *of NS* is from negative infinity to 1. A value of 1 indicates a perfect agreement and a value of 0 indicates that the model predictions are as accurate as the mean of the observed data. A negative value indicates that the model performs worse than the mean of the observed data.

RESULTS AND DISCUSSION

Predictive mathematical modeling

The percentage of non-faecal matter in the pit latrines as adopted from Zziwa et al. (2016) was taken to be 25.8% (Table 1), a value close to what was reported in earlier studies by Bakare (2014) and Still and Foxon (2012). The simulated results from the Equation (6) are shown in Figure 4 and Figure 5. The average sludge accumulation rate according to the developed model was 81 ± 25 litres/ person/ year. The model was calibrated by first removing outliers, that is, values with very high or very low sludge accumulation rates (greater than 350 litres/ person /year or lower than 30 litres/ person/ year). For pits that had values lower than 30 litres/person/year and those greater than 350 litres/per/year, the stated field emptying time

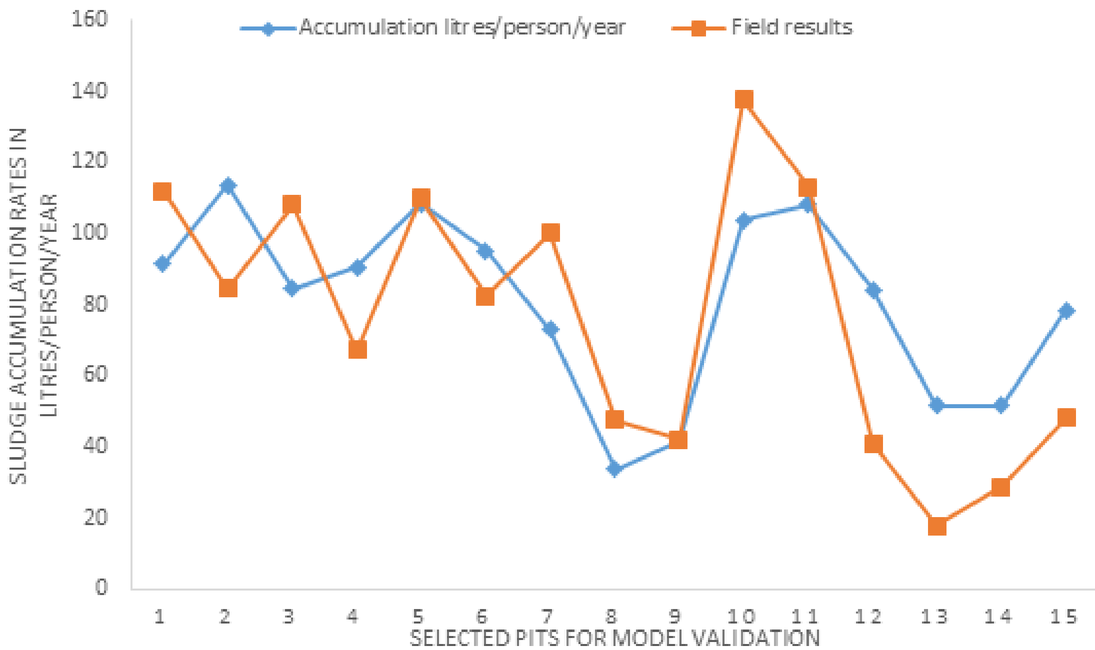

Figure 4. Comparison of simulated and experimental data.

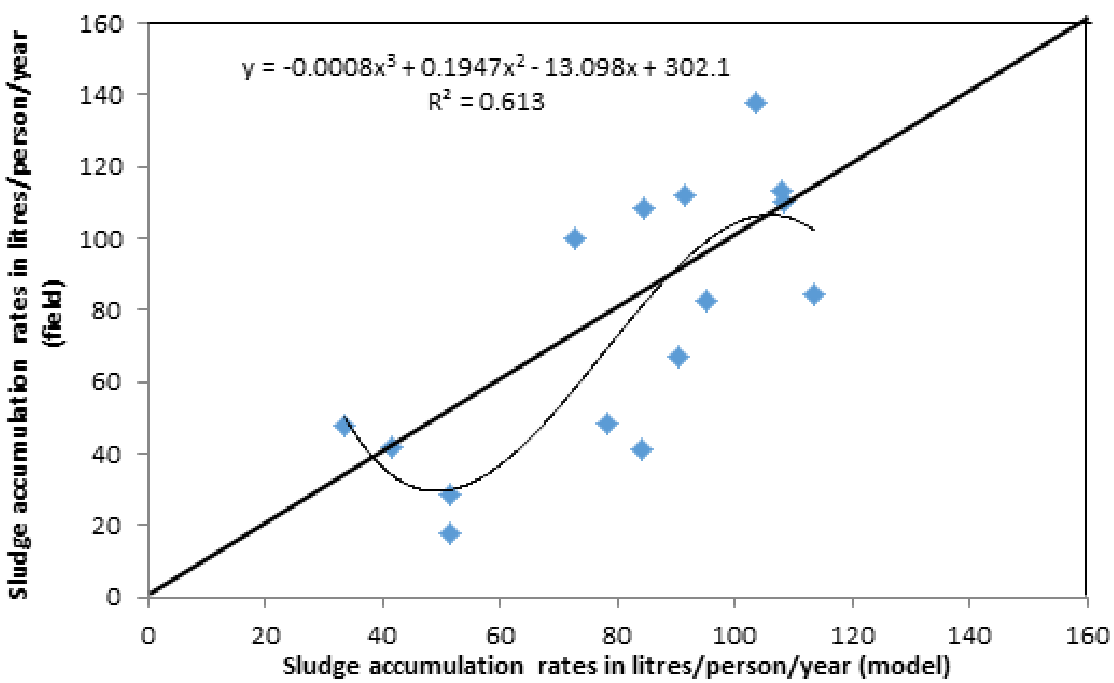

Figure 5. Simulation of model and field results showing R2 value.

was averagely twice a year while that which was calculated was much less (less than 3 months) which meant that some of the information given by the pit users might have been inaccurate. The model parameters were adjusted to ensure that the model fits the data used for its development.

Table 2. Paired t-test for sample means between modelled results and field measurements.

Parameter	Modeled results	Field measurements
Mean	80.64	75.98
Variance	647.37	1354.85
Observations	15	15
Pearson Correlation	0.73	-
Hypothesized Mean Difference	0	-
df	14	-
t Stat	0.72	-
P(T<=t) one-tail	0.24	-
t Critical one-tail	1.76	-
P(T<=t) two-tail	0.48	-
t Critical two-tail	2.14	-

The model value for sludge accumulation rate was almost twice that which was recorded in previous literature (Bakare, 2014; Brouckaert, 2013; Mara, 1984). This was unlike areas were previous studies focused, the pit latrines in the slums selected for this study were designed differently having varying dimensions, sizes, drop holes and found in different geographical locations. The higher value of sludge accumulation rate was mostly contributed by the non-biodegradable content of solid waste deposited in the pits along with faecal matter (Zziwa et al., 2016). This is particularly so because slum areas in Kampala city have a challenge with solid waste management and given that most of the plots of land are small, pit latrines double as rubbish pits as well (Niwagaba et al., 2014; Hoornweg and Bhada-Tata, 2012; Kulabako et al., 2004; Still et al., 2005).

Specific notes for model calibration

The sludge accumulation rates of fifteen out of the thirty five pit latrines simulated by the model were accurately predicted to within 70% - 90%. These pit latrines for which the model performed very well were considered to be ‘good’ pits and had common characteristics of having more than fifteen users (mainly public and rental pit latrines) and the non-faecal material accounted for 25.8% of the total matter in the pit latrine. Outliers (pits whose observed values were higher than 350 litres/person/year and lower than 30 litres/person/year) had to be discarded from the model since these results were not realistic in nature given the parameters involved. For instance, it was unlikely that a pit latrine with less than 10 people could have a sludge accumulation rate of close to 500 litres/ person/ year. This is because with such a value of SAR and given the size of the pit latrines, there would be the need to empty the latrines every week which is not the case in reality. It was suspected that some inaccurate information about the pit characteristics was given during sampling.

Optimization criteria

The developed model may be considered efficient for the predicted model results of the fifteen pit latrines given the Nash Sutcliffe value of 0.52 and the adjusted R^2 value of 0.50. Values of R^2 in ranges of 0.8 and above are considered to be acceptable model accuracy values. However, models that try to predict human behaviour generally have low R^2 values of less than 0.5 (Frost, 2013). The model developed accounted for half the variation in sludge accumulation rates in pit latrines in slum areas. This low value could be attributed to poor pit maintenance and not ensuring that the pit bottoms are not fully sealed. Hence, the observed values could have been impacted upon by geo-physical conditions of the soil and drainage of pit latrine sites (Kulabako, 2005; Kulabako et al., 2007).

Comparison of predicted and experimental data

The model results were compared with the experimental data. Results from a paired t-test showed that the Pearson’s correlation to be 0.73 which indicated a strong relationship between the model and the field results (Table 2). The mean value of the sludge accumulation rates given by the model and that of the field results were comparable as there was no significant difference between them ($p>0.05$) and this means that the model could be used to estimate the sludge accumulation rates in the slum areas. An equality line (1:1 line) was drawn to indicate a measure of agreement between the model and field results. The equality line (Figure 5) showed that the model was a good approximation since it showed an even distribution between the points. The 1:1 line in Figure 5 shows that the model was efficient for values between 40 and 110 litres/person/year. For values below this range, the model is overestimated the sludge accumulation rates while for those above the range, the model is underestimated. This is because the model considered a constant value for the non-faecal matter (Zziwa et al., 2016) which in reality is not the case. Hence, for pits with better use and less non-faecal matter; the model did not capture this and so overestimated the SAR while it underestimated the same for pit latrines that had more non-faecal matter. The developed model was however, found to be a better approximation of sludge accumulation rates in slum areas since it considered solid waste deposited in the pit latrines and was able to cover a range of pit latrines with different designs and user behaviour unlike previous studies that had been carried out (Brouckaert, 2013; Bakare, 2014; Murphy, 2015). The model was found to be a better approximation for rentals and public pit latrines compared to the private pit latrines, given their numbers were more in the study.

CONCLUSION AND RECOMMENDATIONS

The average sludge accumulation rate determined by model was 81 $\pm$ 25 litres/person/year. Model validation showed that the developed model was 52% efficient and accounted for 50% of the variation in the sludge accumulation rates. The model is sufficient for prediction of filling rates in the public and rental pit latrines within the studied slums given the variation in pit latrine designs, user behaviour, pit dimensions, location and solid waste deposal patterns. The model can therefore be adequately used for prediction of sludge accumulation rates of lined pit latrines in slum areas. The model was found to have limitations for determining sludge accumulation rates for private pit latrines and those pits that are managed properly. This study did not provide a specific emptying plan for each pit latrine but with the information provided on the sludge accumulation rates and the estimates provided, each pit latrine owner is able to adequately plan for emptying, given the different sizes of the pit latrine. Further studies can be taken on the effect of geo-physical factors such as soil characteristics and drainage patterns on sludge accumulation rates and a study to model sludge accumulation rates in unlined pit latrines in the slum areas. .

Conflict of interest

The authors have not declared any conflict of interest.

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