Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 4, Issue 08, pp. 130-134. August, 2012

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

MASS BALANCE MODEL FOR SLUDGE ACCUMULATION IN SEPTIC TANKS

Nnaji, Chidozie Charles* and Agunwamba, Jonah Chukwuemeka

Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria

ARTICLE INFO

Article History:
Received 18th June, 2012
Received in revised form
29th July, 2012
Accepted 25th August, 2012
Published online 29th September, 2012

Key words:
Sludge depth,
Septic tank,
Time of operation.

ABSTRACT

Sludge accumulation in septic tank was modeled using material balance. A second order ordinary differential equation was obtained which was then solved under stipulated initial conditions. The model is an exponential function which relates sludge depth (y) to time of operation (t) and the plan area of tank. The model was calibrated using data from four different septic tank audits spanning six months to eight years obtained from literature and involving over 1000 septic tanks. A correlation coefficient of R = 0.985 was obtained between measured sludge accumulation and model results. The model obtained was compared with two existing models, namely: Weibel's model derived in 1955 for the US Public Health Service, and Bound's model of 1995. The sludge accumulation model was then modified to account for scum accumulation on the air-water interface of the septic tanks.

INTRODUCTION

Septic tank is designed to collect wastewater, segregate settleable and floatable solids (sludge and scum), accumulate, consolidate and store solids, digest organic matter and discharge treated effluent (Bounds, 1997). Sludge accumulation and digestion in septic tanks form a very critical and integral part of the operation of the system. For a properly designed and maintained septic tank, sludge accumulation tends to be the limiting factor for effective performance. Sludge accumulation results from the settling of solids on the bottom of the tank. The treatment quality of the tank is greatly diminished when excess sludge and scum accumulate in the tank so that they start to be carried over into the absorption field. Excess solid particles leaving the septic tank plug up the leaching pipes and then there is no adequate distribution of the effluent and no proper treatment of the waste in the drain field. For effective operation, the septic tank should have both adequate detention time for solids separation and enough volume for long term storage of sludge. Longer storage periods for sludge (desludging interval) allows enough time for maximum biodegradation. Jowett (2007) noted that the conventional septic tank with air space experiences more sludge accumulation than long, shallow, narrow septic tank without air space. Air - water interface actually encourages vegetative moulds that trap sludge particles rising on fermentation bubbles, creating a hard leathery scum layer which could overturn and sink, causing resuspension and outflow of sludge (Jowett, 2007; Dunbar, 1907). However, it is counterproductive to recommend that septic tanks be constructed without air space since the reserve space will always be a functional component of the septic tank. Without the reserve space, any blockage will result in the backup of sewage into the building. Paing *et al.* (1999) and Caselles-Osarios *et al.* (2007) found that more sludge accumulated at the inlet than at the outlet due to higher methanogenic activities towards the outlet for anaerobic lagoon and constructed wetlands respectively. While Jowett (2007) reported that volatile fatty acids generally increase from inlet to outlet, Paing *et al.* (1999) reported a decrease in volatile fatty acid from inlet to outlet. Even though the septic tank system is one of the most widely used onsite wastewater treatment system, it usually suffers from poor performance and even complete failure due to gross neglect. Al-Layla and Al-Rawi (1989) observed that some of the septic tanks monitored in the Mosul city of Iraq experienced rapid filling with sludge, thus necessitating desludging within short intervals ranging from two weeks to six months. Sludge accumulation is not entirely undesirable. Laak and Crates (1978) observed that 10% to 30% of the total organic nitrogen is removed by sludge storage in the septic tank.

Sludge accumulation in various sludge retaining wastewater treatment facilities have been found to range between 0.004m^3/capita/year to 0.148m^3/capita/year (Picot *et al,* 2003; Picot *et al*, 2005). However, these values seem to give the impression that sludge accumulation is occurs at a constant rate. This would have been the case but for the simultaneous consumption of a fraction of accumulated sludge by micro-organisms. Hence there is need for a sludge accumulation model for the estimation of accumulated sludge. There are numerous studies dealing with sludge accumulation in septic waste stabilization ponds. One of such is that by Saqqar and Pescod (1995) in which they developed a model (Equation 1) for sludge accumulation in anaerobic ponds using mass balance approach.

$$V_{AS} = K_{AS}\left[\left(1.7F_{XVSS,0} + 4.5F_{XFSS,0} + F_{CBOD,0}\right)/1000\right] \qquad (1)$$

***Corresponding author:** Chidozie.nnaji@unn.edu.ng; jcagunwamba@yahoo.com;

Where K_{AS} is called the sludge accumulation coefficient which is a measure of the biodegradability of the sludge accumulated. They observed that the value of K_{AS} will keep decreasing until a constant value is obtained at the completion of decomposition. However, there are not many studies dealing with sludge accumulation in septic tanks. This may be as a result of the fact that there is a move away from the use of septic tanks to central treatment systems in most advanced countries. However, most people in developing countries still rely on the septic tank system as a sanitation facility. In fact, the septic tank is some sort of luxury in many third world countries as many of the masses cannot afford it and still rely on old fashioned sanitation methods. In most places where septic tanks are used, there are reports of poor performance resulting from poor maintenance with excessive sludge accumulation being prominent. Of the 48 septic tanks studied by Ahmed et al. (2005), 32(67%) needed cleaning out, 23(48%) had soggy absorption fields, 4(8%) had structural defects such as broken baffles or lids, 2(4%) had technical faults such as high water table or the absorption system being too close to a water well, 3(6%) had insufficient capacity, and only 7(15%) were well maintained. It is therefore necessary to model sludge accumulation in septic tanks in order to effectively predict safe desludging intervals for optimum performance of septic tanks. The most popular equations (Equations 2 and 3) for estimating sludge and scum accumulation in the septic tank were obtained by Bounds (1995) and Weibel *et al.* (1955) respectively.

$$N = 47t^{0.675} \quad (2)$$

$$N = 13.39t + 50.86 \quad (3)$$

Where N = volume of septage accumulated in tank in US gallons per capita and t = number of years of operation. These equations are purely empirical in nature and have a statistical confidence level of 95%, and predict the gallons per capita accumulated after any time given in years. In this study, we have adopted a mass balance approach to model sludge accumulation in septic tanks.

MODEL FORMULATION

A model for predicting sludge accumulation in the septic tank was formulated using material balance. Consider a septic tank receiving an influent of fairly constant settleable solids concentration (QC_0) but gives an effluent of variable concentration of settleable solids (QC_t). The idea is that as sludge accumulates in the tank, the detention time reduces such that effluent concentration of solids increases with time.

Figure 1: Mass Balance of Solids in the Septic Tank

The mass of sludge dM accumulated in the tank in time dt can be expressed as follows.

$$\frac{dM}{dt} = QC_0 - QC(t) \quad (4)$$

If we consider the fact anaerobic decomposition will normally reduce the volume of the accumulated sludge by 40 to 50% producing methane (CH_4), carbon IV oxide (CO_2), water(H_2O) and hydrogen sulphide (H_2S) gases (Seabloom *et al.*, 1982), then Equation (4) translates to

$$\frac{dM}{dt} = QC_0 - QC(t) - k(QC_0 - QC(t)) \quad (5)$$

M = mass of sludge accumulated at time t
Q = Flow rate (m^3/s)
C_0 = Influent concentration of settleable solids (*mg/l*)
C = Effluent concentration of settleable solids (*mg/l*)
k = rate constant of degradation by bacteria(day^{-1})

However, even though the bacteria converts some sludge to gas thus reducing the quantity of sludge in the tank, the bacteria will multiply as they consume the sludge so that the net quantity of sludge actually converted to sludge is given by
Net decrease in sludge mass = Mass of sludge consumed by bacteria - Increase in bacteria mass. But increase in bacteria mass is proportional to mass of sludge consumed ie

$$\frac{dX}{dt} = \lambda k(QC_0 - QC(t)) \quad (6)$$

Where λ = Yield coefficient (no unit)

Therefore

$$Net\,decrease\,in\,sludge\,mass = (QC_0 - QC(t))(\lambda k - k) \quad (7)$$

Rewriting Equation (5) to incorporate bacteria mass contributing to sludge mass, Equation (5) becomes

$$\frac{dM}{dt} = QC_0 - QC(t) - k(QC_0 - QC(t)) + \lambda k(QC_0 - QC(t)) \quad (8)$$

Since the concentration of effluent solids increases as sludge accumulates in the tank i.e., increase in effluent concentration of solids is proportional to sludge accumulation. This can be expressed mathematically as

$$\frac{dC}{dt} = \sigma \frac{dM}{dt} \quad (9)$$

Where σ is a proportionality coefficient

Equation (9) follows from the result obtained by Heins *et al.* (1999) as shown below.

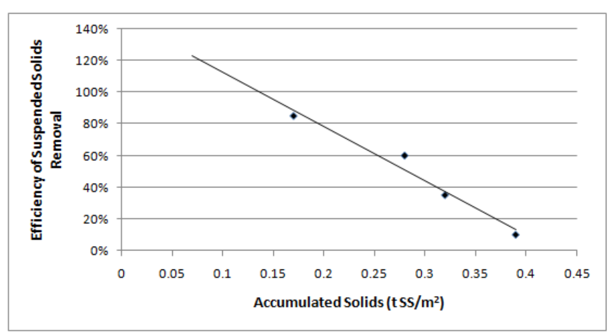

Fig. 2: Accumulation of Sludge versus Efficiency of SS Removal Plotted from Data Obtained by Heinss *et al.* (1999)

Figure 2 can be generalized as shown follows

$$M = \alpha - \gamma n \tag{10}$$

M = mass of sludge
α = intercept (having a dimension of mass)
n = efficiency of solids removal (no unit)
γ = slope (having the unit of mass)

$$M = \alpha - \gamma\left(\frac{C_0 - C}{C_0}\right) \tag{11}$$

C_0 = Influent concentration of settleable solids (*mg/l*)
C = Effluent concentration of settleable solids (*mg/l*)

Recalling that $\frac{dC}{dt} = \sigma \frac{dM}{dt}$ then $\frac{dM}{dC} = \frac{1}{\sigma} = \frac{\gamma}{C_0}$

This implies $\sigma = \frac{C_0}{\gamma}$ (12)

Knowing C_0, γ can be determined from the graph M versus C and hence σ can also be determined. The unit of σ is m^{-3}

Hence $\frac{dC}{dt} = \frac{C_0}{\gamma}\frac{dM}{dt}$ (13)

Differentiating Equation (8) yields Equation (14) below

$$\frac{d^2M}{dt^2} = Q(k - \lambda k - 1)\frac{dC}{dt} \tag{14}$$

Substituting Equation (13) in Equation (14) gives Equation (15) below

$$\frac{d^2M}{dt^2} = Q\frac{C_0}{\gamma}(k - \lambda k - 1)\frac{dM}{dt} \tag{15}$$

Let $Q\frac{C_0}{\gamma}(k - \lambda k - 1) = \beta$ (16)

Hence $\frac{d^2M}{dt^2} = \beta\frac{dM}{dt}$ (17)

At the start of operation, the septic tank does not produce effluent until after some days depending on the flow rate and the effective volume of the tank. Before effluent is produced the rate of change of the tank content with time is equal to the flow rate. Hence

$$\frac{dV}{dt} = Q \Rightarrow dV = Qdt \tag{18}$$

V = volume of tank (m^3)
t = time (days)
Q = flow rate of sewage (m^3/s)

Since the plan area of the tank is roughly constant, Equation (18) becomes

$$dy = \frac{Q}{A}dt \tag{19}$$

A = plan area of tank (m^2)

Integrating Equation (19) between the limits $y(0) = 0$ and $y(t_e) = h_e$ ie t_e is the time the contents (both liquid and solids) of the tank reach the height (h_e) of the effluent pipe. This is equal to the time it takes the tank to produce effluent. Hence

$$h_e = \frac{Q}{A}t_e \Rightarrow t_e = \frac{Ah_e}{Q} \tag{20}$$

At time t_e, the amount of sludge in the tank (assuming that before effluent is produced, all the solids in the tank would have settled) is given by

$$M(t_e) = QC_0t_e = C_0Ah_e.$$

This is the first initial condition ie when $t = t_e$, $M = C_0Ah_e$

For the second initial condition, we refer to Equation (8). Neglecting the action of bacteria at the time the tank is just about to start producing effluent; Equation (8) reduces to

$$\frac{dM}{dt} = QC_0 - QC(t) \tag{21}$$

At time t_e $QC(t)$ is equal to zero, therefore

$\left(\frac{dM}{dt}\right)_{t_e} = Q(C_0 - C_e)$ This is the second initial condition ie when $t = t_e$, $\frac{dM}{dt} = QC_0 - C_e$ where C_e is the initial concentration of suspended solids in the effluent just as it starts producing effluent. At this stage, the tank should be performing at its optimum.

Solving Equation 17 under the stipulated boundary conditions, we obtain Equation 22

$$M = C_0(Ah_e - \frac{Q}{\beta}) + \frac{Q}{\beta}C_e + \frac{Q}{\beta}(C_0 - C_e)e^{\beta(t - t_e)} \tag{22}$$

If the initial efficiency of the septic tank is given by $\eta = \frac{C_0 - C_e}{C_0}$, then

$$M = C_0(Ah_e - \frac{Q}{\beta}) + \frac{Q}{\beta}C_e + \frac{Q}{\beta}(C_0 - C_e)e^{\beta(t - t_e)}$$

$$M = C_0Ah_e + \frac{Q\eta C_0}{\beta}(\frac{e^{\beta t}}{e^{\beta t_e}} - 1) \tag{23}$$

But $t_e = \frac{V}{Q}$ = initial detention time (θ_i) of the tank. We refer to "initial" detention time because the tank has a maximum detention time at the start of operation. However, there is a reduction in this maximum value as sludge accumulates in the tank. Hence

$$M = C_0Ah_e + \frac{Q\eta C_0}{\beta}(\frac{e^{\beta t}}{e^{\theta_i}} - 1) \tag{24}$$

Since not all the settled solids are biodegradable, a term shall be introduced to take care of the accumulation of this non-biodegradable fraction. Equation (24) is therefore modified as follows:

$$M = C_0 Q\chi t + C_0 Ah_e + \frac{Q\eta C_0}{\beta}\left(\frac{e^{\beta t}}{e^{\theta_i}} - 1\right) \quad (25)$$

Where χ is the fraction of settled solids that are non-biodegradable which has a value of about 0.1 (Agunwamba, 2001). Equation 25 above shows the rate of sludge accumulation with time in the septic tank. But our interest lies in knowing the sludge level or volume of sludge at any future time from the start of operation. Hence, the equation shall be rewritten in terms of *y*. Since the sludge is oversaturated with water, the density of the mixed liquor is given as follows:

$$\rho_{ml} = SG\rho_w(1 - w) \quad (26)$$

Where

ρ_{ml} = density of mixed liquor (Kg/m^3)

ρ_w = density of water = $1000 Kg/m^3$

SG = specific gravity of sludge (no unit)

w = water content of mixed liquor (no unit)

Hence
$$V = \frac{\left[C_0 Q\chi t + C_0 Ah_e + \frac{Q\eta C_0}{\beta}(e^{\beta(t-\theta_i)} - 1)\right]}{1000SG(1-w)} \quad (27)$$

Or in terms of sludge depth

$$y = \frac{\left[C_0 Q\chi t + C_0 Ah_e + \frac{Q\eta C_0}{\beta}(e^{\beta(t-\theta_i)} - 1)\right]}{1000SG(1-w)A} \quad (28)$$

Equation 22 represents the model for sludge accumulation in septic tanks where all parameters remain as previously defined.

Model Calibration

The sludge accumulation model (Equation 28) was calibrated using the sludge accumulation data obtained from literature. Table 1 is a summary of data sources used and the time length of septic tank sludge accumulation monitoring. The water content *w* and specific gravity *SG* of sewage sludge is 0.88 and 1.03 respectively (Saqqar and Pescod, 1995). The calibration was done by filling a column in Microsoft Excel with time values ranging from half a year to 9 years which roughly covers the duration of the sludge accumulation study. The next column was filled with an arbitrary constant value for β. The third column was programmed to use the corresponding time value of the first column and the arbitrary value of β to evaluate the generalized sludge accumulation model of Equation 28. The fourth column was filled with the sludge accumulated per capita corresponding to the time of measurement in the first column. Scatter plots of the measured sludge accumulation versus time and that of the calculated sludge accumulation versus time were made. The value of β was manipulated until the two curves came the closest. The final curve is shown in Figure 3. Hence Equation (29) was obtained with a correlation coefficient of 0.985.

$$V_{sludge} = 0.00832 + 0.011t - 0.56(e^{-0.11t} - 1) \quad (29)$$

Where V_{sludge} is the volume of sludge in m^3/capita accumulated in time *t* years.

Table 1: Sludge Accumulation Data

Time (Years)	Volume of Sludge Accumulated (m^3/capita)	Period of Monitoring	No of Septic Tanks	Source
0.5	0.046	5 years	28	Gary (1995)
1	0.047	3 years	727	Bounds (1994)
2.8	0.174	8 years	486	Bound (1990)
4.8	0.29	8 years	486	Bound (1990)
5	0.325	5 years	28	Gary (1995)
8	0.378	8 years	486	Bound (1990)

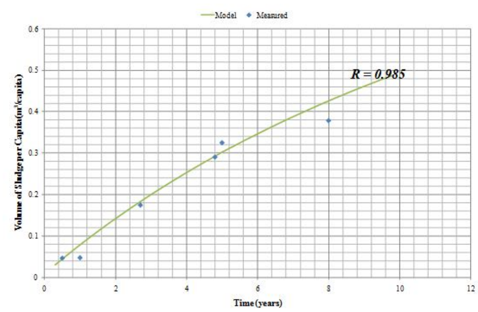

Figure 3: Plots of Model and Measured Sludge Accumulation versus Time

In order to obtain the total volume of septage (sludge and scum) in the tank at any time, Equation 29 was modified to include a scum accumulation term. The Douglas County Audit found that, the scum accumulation was 12 *US gallons/capita/year* (0.0454m^3/capita/year) in the first year and a constant rate of 2.6 *US gallons/capita/year* (0.0098m^3/capita/year) in subsequent years. This rate of scum accumulation was corroborated by a 3-year audit of 727 septic tanks by the Montesano Community, Washington at 95% confidence level (Bounds, 1994). Hence, the rate of scum accumulation can be given as:

$$V_{scum} = 0.035 + 0.01t \quad (30)$$

Where V_{scum} is the volume of scum in m^3 per capita and *t* is time in years. Equation 29 is then merged with Equation 30 to yield Equation 28 for the total volume of solids (septage) accumulated in the tank in time *t* (years).

$$V_{septage} = 0.043 + 0.021t - 0.56(e^{-0.11t} - 1) \quad (31)$$

The total depth occupied by solids is given by Equation 32.

$$y_{septage} = \frac{0.043 + 0.021t - 0.56(e^{-0.11t} - 1)}{A} \quad (32)$$

Comparison of Model with Existing Sludge Accumulation Models

It is necessary to compare the model (Equation 28) for solids accumulation derived in this study with the existing models. The most popular models for solids accumulation are those of

Bounds (1995) and Weibel *et al.* (1955) derived for the US Public Health Service.

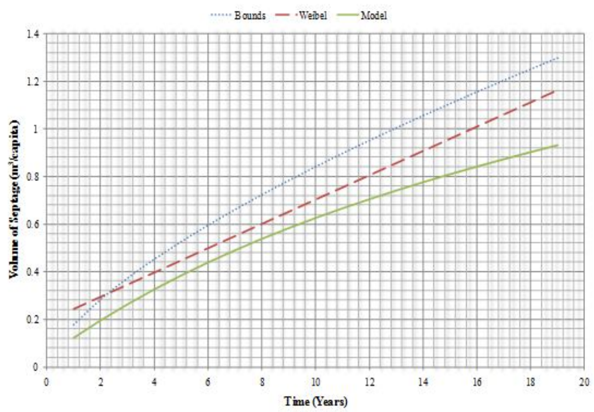

Figure 4: Comparison of Model with Bounds' and Weibel's Models

Figure 4 shows that the new model gives lower estimates than the models of Bounds and Weibel *et al.* But Seablom *et al.* (2004) noted that Bound's equation gives high estimates of septage accumulation. Weibel's equation has the disadvantage of suggesting that sludge accumulation is a linear. Sludge accumulation studies have shown that this is not the case as a result of consolidation and decomposition of accumulated sludge by micro-organisms, thus imparting on the process a substantial element of nonlinearity. The aspect of solids accumulation that can be reasonably assumed to have a constant rate is scum accumulation and the accumulation of non-biodegradable fractions of sewage. This has been reflected in our model. Equation 32 gives the average depth of sludge and scum in the septic tank at any time since it is already known that sludge accumulation increases from the inlet to the outlet. Knowledge of the depth of sludge at any given time helps in determining desludging intervals for septic tanks. This is very important especially in localities where sludge measuring devices are not available. Equations 27 and 28 can also be applied to other wastewater treatment facilities such as the waste stabilization pond and constructed wetland where data are available.

REFERENCES

Ahmed, W., Neller, R. and Katouli, M. (2005). Evidence of septic system failure determined by a bacterial biochemical fingerprinting method. *Journal of Applied Microbiology*, 98, 910 – 920.

Al-Layla, A. M. and Al-Rawi, S. M. (1989). Evaluation of septic tank performance in some parts of Mosul City in Iraq. *Journal of Environmental Science and Health*, Part A, 24 (5), 543 – 556.

Bounds, T. R. (1995). Septic tank septage pumping intervals, Proceedings 8th Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition, University of Washington, Seattle, WA.

Bounds, T. R. 1997. Design and performance of septic tanks. Conference of the American Society for Testing and Materials, Philadelphia, Pennsylvania.

Caselles-Osarios, A., Puigagu, J., Segu, E., Vaello, N., Granes, F., Garcia, D. and Garcia, J. (2007). Solids Accumulation in Six Full Scale Subsurface Constructed Wetlands. Water Research, 41, 1388 – 1398.

Dunbar, W. (1907). Principles of Sewage Treatment. Translated in 1908 by H.T. Calvert. Griffin, London

Gary, F. N. (1995). The influence of sludge accumulation rate on septic tank design. *Environmental Technology* 16 (8), 795 – 800.

Heinss, U., Larmie, S. A. and Strauss, M. (1999). Characteristics of Fecal Sludges and their Solids-Liquid Separation. SANDEC/EWAG, January 1999.

Jowett, E. C. and Lay, R., in Press. Comparative performance of closed-conduct, laminar flow septic tanks. Submitted to *Small Flow Quarterly*, University of West Virginia, 2005.

Jowett, E. C., (2007). Comparing the performance of prescribed septic tank to long, narrow, flooded design. Presented at 2007 WEFTEC Technical Program 16. San Diego CA.

Paing, J., Picot, B., Sambuco J. P. and Rambaud A., (1999). Sludge accumulation and methanogenic activity in anaerobic lagoon. *Water Science and Technology*, 42 (10 – 11), 247 – 255.

Picot, B., Paing, J., Sambuco, J. P., Costa, R. H. R. and Rambaud, A. Biogas production, sludge accumulation and mass balance of carbon in anaerobic ponds. Water Science and Technology, 48 (2), 243 – 250.

Picot, B., Sambuco, J. P., Brouillet, J. L. and Riviere, Y. (2005). Wastewater stabilisation ponds: sludge accumulation, technical and financial study on desludging and sludgedisposal case studies in France. Water Science and Technology, 51 (12), 227 –234.

Saqqar, M.M. and Pescod, M.B. (1995b). Modelling sludge accumulation in anaerobic wastewater stabilization ponds. Wat. Sci. Tech., 31(12), 185–190.

Seabloom, R. W., Bounds, T., and Loudon, T. (2004). Septic Tanks http:/./www.onsiteconsortium.org./files/septic tanks paper.pdf62p

Weibel, S. R., Bendixen, T. W. and Coulter, J. B. (1955). Studies on household sewage disposal systems, Part III," U.S. Public Health Service Publication No. 397.

Winneberger, J. H. T., (1984). "The Septic Tank". In Septic Tank Systems, a Consultant's Toolkit. Volume II.

****