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Detention Time as a Critical Parameter in Septic Tank Design

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Abstract: In order to reveal the importance of detention time in septic tank design, an expression was derived to show the relationship between detention time and sludge level. Charts that show the decline of detention time with sludge accumulation were produced. These charts show that the usual recommendation that septic tanks be desludged when they are one-third full could be irrational most of the time. It was shown that a tank that is one-third full may still have enough residual detention time for optimal performance. A more rational approach is that septic tanks should be desludged when they no longer have enough detention time for efficient performance. It was also shown that water use should be given serious attention in septic tank design as it can have serious consequences for detention time.

Key words: Septic tank, detention time, sludge accumulation, desludging.

Introduction

The septic tank system is the most widely used onsite treatment system for domestic wastewater. In fact, most developing countries (Nigeria included) lack the technology and economic power to construct and operate sewerage systems for conveyance of domestic wastewater to central sewage treatment facilities; so masses rely on the septic tank system for sewage treatment. It is an enclosed receptacle designed to collect wastewater, segregate settleable and floatable solids (sludge and sum), accumulate, consolidate and store solids, digest organic matter and discharge treated effluent (Bounds, 1997). In the United States only, over 50 million people use the septic system. According to Burubai et al., 2007, over 46% of the Nigerian population use the septic tank system. The septic tank system was once thought to be a temporary solution to domestic wastewater treatment and disposal. This was true until 1997 when the United States Environmental Protection Agency and Congress officially recognized the system as a viable, long-term solution for treating wastewater. All things being equal, the septic tank system does not pose much problem and requires little maintenance. However, when the system is not working properly, it merely serves as a route for recycling pathogens and deadly chemicals through the ecosystem. Nearly 40% of groundwater attributed disease outbreaks can be traced to the failure of onsite disposal systems. Weissman et al. (1976) and Taylor et al. (1981), among others, reported cases of disease outbreak resulting from groundwater contamination due to septic tank failure.

Detention of waste tends to homogenize the flow of waste water to the drain field (Baumann et al., 1978). Detention also provides some time for biodegradation by anaerobic micro-organisms. However if the septic tank does not function properly, there will be a short circuit causing some particles to leave the tank in a period less than the design detention time. There will also be dead zones where some particles seem to lodge permanently thereby reducing the effective volume of the tank and hence reducing the detention time. Bounds (1997)

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observed that regardless of number, size or shape of supplemental compartments, the primary or first compartment's capacity should be defined based on hydraulic loading, velocity through the tank, reserve capacity, solids storage capacity and hydraulic retention time. Hydraulic retention time is a function of wastewater flow; however, wastewater flow varies from one septic tank to the other. The average wastewater flow reported by various researchers are 160 lpcd, 24 lpcd, 71 lpcd, 51 lpcd, 29 lpcd (Watson et al., 1967), 64 lpcd, 100 lpcd and 120 lpcd (Rahman et al., 1999).

Several authors were of the opinion that in order to optimize separation of solids and to maximize retention time without short-circuiting, the tank should encourage a well developed laminar flow regime. Rahman et al. (1999) recommended a five-day retention time for septic tanks receiving only toilet wastewater, a three-day retention time for septic tanks receiving toilet wastewater and kitchen wastewater, and one day detention time for an all purpose septic tank. For the baffled anaerobic septic tank, Nguyen et al. (2007) found that the optimum hydraulic retention time is 48 hours as increasing the retention time beyond this will require more cost in terms of tank volume while at the same time not producing any significant result above that observed for 48 hours hydraulic retention time. A closer look at the results of Koottatep et al. (2004) revealed that improved septic tanks performed much better than the conventional septic tanks at low detention times, such as 24 hours. However, as the detention time increased the performance of the conventional septic tanks improved and even recorded a better performance in SS removal than the three baffled reactors. Septic tanks can achieve high levels of pollutant removal due to long detention times (Al-Layla and Al-Rawi, 1989). Inadequate detention time will grossly reduce the performance of septic tanks. However, using very high detention times in septic tank design will amount to excessive tank volume which will be uneconomical. Our choice of detention time as a critical parameter for septic tanks is because of the interwoven relationship between detention time and sludge accumulation which, in turn, is interwoven with influent and effluent solids. In fact, Philip et al. (1994) revealed that total solids is one of the best indicators of septic tank failure.

Methodology

Depreciation of Detention Time and Rate of Settling

As the mass of sludge in the tank increases, the detention time decreases. Thus

$$\frac{dM}{dt} \propto -\frac{d\theta}{dt} \tag{1}$$

$$\frac{dM}{dt} = -K_s\frac{d\theta}{dt} \tag{2}$$

where K_s = proportionality coefficient (having the dimension of mass) and θ = detention time of tank at any time t.

$M = 1000SG\,(1 - w)V$ where V is the total volume occupied by the mixed liquor of sludge and water. The above equation can be rewritten as follows:

$$M = 1000SG\,(1 - w)(V_t - V_l) \tag{3}$$

where SG = specific gravity of sewage sludge, w = water content of sludge, V_t = design volume of tank and V_l (residual volume) = volume of tank above sludge layer.

But $V_l = \theta Q$,

hence $$M = 1000SG(1 - w)(blh - Q\theta) \tag{4}$$

Differentiating Equation (4) yields

$$dM = -1000SGQ(1 - w)d\theta \tag{5}$$

Comparing Equation (1) and Equation (5) shows that $K_s = 1000SGQ(1 - w)$ where K_s represents a form of settling rate having a dimension of MT^{-1}. The water content w and specific gravity SG of sewage sludge is 0.88 and 1.03, respectively. Hence

$$K_s = 123.6Q \tag{6}$$

Integrating Equation (5) under the boundary condition $M(0) = 0$ and $\theta(0) = \theta_i$, where θ_i is the initial (design) detention time of the tank; and combining with Equation (6), we have

$$M = 123.6Q\,(\theta_i - \theta) \tag{7}$$

Equation (7) shows that the mass of sludge accumulated in the septic tank uses up a fraction of the original detention time of the tank. This implies that its detention time starts declining immediately the tank goes into operation. We shall then proceed to derive an expression that relates decline in detention time with time of operation of septic tanks.

$$V = ybl = Q(\theta_i - \theta) \tag{8}$$

where V = volume occupied by sludge (m^3), y = depth of sludge (m), b = width of tank (m) and l = length of tank (m). All other parameters have previously been defined. Hence

$$y = S_o(\theta_i - \theta) \tag{9}$$

where y = depth of sludge and $S_o = Q/bl$ which is the overflow rate. Equation (9) relates loss of effective detention time to sludge accumulation. Equation (9) can be rewritten as follows:

$$y = \frac{blH_{re}}{bl\theta}(\theta_i - \theta) \tag{10}$$

H_{re} = residual depth above sludge layer (m)

$$y\theta + H_{re}\theta = H_{re}\theta_i$$

$y + H_{re}$ = total effective height of tank (h_e) which is the same as the height to the effluent pipe; hence,

$$\theta = \left(1 - \frac{y}{h_e}\right)\theta_i \tag{11}$$

Nnaji and Agunwamba (2011) derived a generalized mass balance expression for sludge depth in septic tank given as

$$y = \frac{\left[C_0 Q\chi t + C_0 A h_e + \frac{Q\eta C_0}{\beta}\left(e^{\beta(t-\theta_i)} - 1\right)\right]}{1000SG(1-w)A} \tag{12}$$

They calibrated the model to obtain

$$y_{septage} = \frac{0.043 + 0.021t - 0.56(e^{-0.11t} - 1)}{A} \tag{13}$$

By substituting Equation (13) in Equation (11), we obtain a relationship between sludge depth and residual detention time.

$$\theta = \left(1 - \frac{0.043 + 0.021t - 0.56(e^{-0.11t} - 1)}{Ah_e}\right)\theta_i \tag{14}$$

Equation (14) represents decay of detention time and will enable anyone to assess the decline of detention time as sludge accumulates in the tank. Sludge accumulation reduces the effective volume of the tank so that the detention time available for solids separation is reduced in turn. Equation (11) can be re-written as follows.

$$\theta = \left(1 - \frac{0.043 + 0.021t - 0.56(e^{-0.11t} - 1)}{Q\theta_i}\right)\theta_i \tag{15}$$

This is because Ah_e is the initial effective volume of the tank which is equal to the product of wastewater flow and initial detention time. Hence

$$\theta = \theta_i - \frac{0.043 + 0.021t - 0.56(e^{-0.11t} - 1)}{Q} \tag{16}$$

Equation (16) relates *residual detention time* to time of tank operation. This can be very useful in ascertaining whether the septic tank still has enough detention time for efficient performance.

Discussion

Many codes and designers recommend that the septic tank should be desludged when sludge has reached one-third of the tank height. But this has no rational basis. The most critical parameter in septic tank design and operation is the detention time. At any point in time, the detention time must be sufficient to allow solid particles to settle, otherwise, its performance will be impaired. Desludging interval of the septic tank should rather be based on a minimum *residual detention time*. This is the minimum allowable detention time in the septic tank. It is the detention time which should be specified by the designer such that once it is attained, the tank must be desludged. Research has shown that detention time between 12 hours and 24 hours are close to the threshold of acceptable solids removal in the septic tank. Equation (11) relates residual detention time to the ratio of sludge depth to tank effective height. In order to expose the arbitrariness in the recommendation that septic tanks be desludged after five years (Philip et al., 1994) or when sludge depth reaches one-third of the effective height, a plot of residual detention time and the ratio of sludge depth to tank height is presented in Figure 1 based on Equation (11).

From the figure, it can be seen that if the initial detention time of a septic tank is two days, at a sludge depth to effective height ratio of 0.3 the tank will still have adequate detention time of 1.4 days. Desludging the tank at this stage will tantamount to waste of time and money. It will be more rational if the designer sets a minimum residual detention time of say one day, then the tank will be due for desludging at a sludge depth to effective height ratio of 0.76 which will take a longer time to attain. This approach has the advantage of both economy and efficiency in that it ensures that the tank is not desludged prematurely resulting in waste of resources. It also ensures that the tank is still performing within acceptable limits at the time of desludging. The

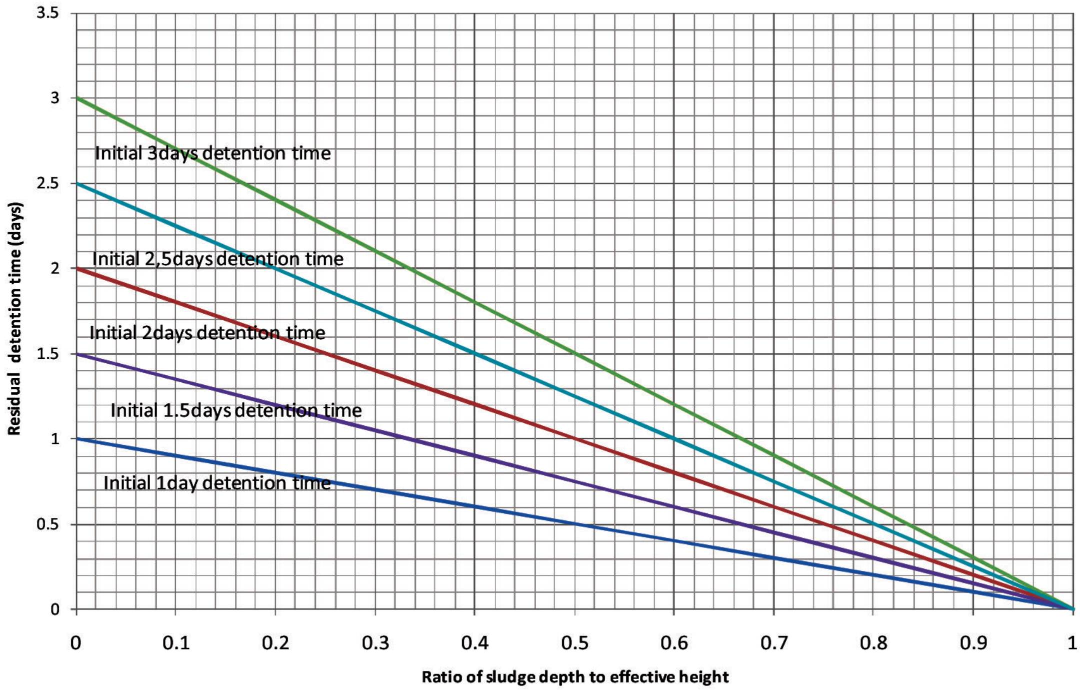

Figure 1: Decline of detention time with sludge accumulation.

other extreme of irrationality in septic tank issues is waiting for the tank to fill up and refuse to take in more sewage or even result in the back up of sewage into the house. While the practice previously mentioned leans to the side of safety though uneconomical, this particular practice is neither safe nor economical because this can shorten the life span of the septic tank as well as result in the clogging of the drainfield or soak pit.

Another anomaly in the prevailing design approach of septic tanks is that most times, consideration is not given to water use and availability in the house. It is not just enough to know the number of people that are likely to live in the house, it is important to know the rate of water consumption. Table 1 shows the variation in water consumption per capita for different water supply conditions.

Water consumption will determine the capacity of septic tank to use. Even though water consumption varies from house to house, the raw sewage flow per person into the tank will not vary much. A superficial reasoning will lead to the conclusion that a house with low water consumption will require a septic tank with low detention time. But this is not the case because a low detention time coupled with very low wastewater flow rate will yield an insignificant design volume that will soon be filled up with solids. This is because, even though water use may vary widely from place to place, the average feaces input per person into the tank does not vary

Table 1: Water consumption under different supply conditions

Water supply condition	*Water use (lpcd)*	*Source*
Public standpipe farther than 1 km	≤ 10	Gleick (1996)
Public standpipe closer than 1 km	20	Gleick (1996)
House connection, simple plumbing, pour, flush toilet	80*	Gleick (1996)
Urban house connection with garden	275*	Gleick (1996)
Nigerian average water use	36	UNDP (2006)
Basic water requirement	50	Gleick (1996)

* Represents average value.

significantly. Very small septic tank volumes lead to frequent need for desludging and hence high cost of maintenance. Figures 2 to 5 produced from Equation (16) show how wastewater flow affects *residual detention time*. It should be noted that the wastewater flow is taken as 80% of the total water consumption per person per day.

These figures demonstrate vividly that houses with high water consumption or wastewater flow can have tanks with moderate to low detention times and still operate for a long time without requiring desludging. Figure 3 shows that a septic tank designed for a house with full water connections and having an initial

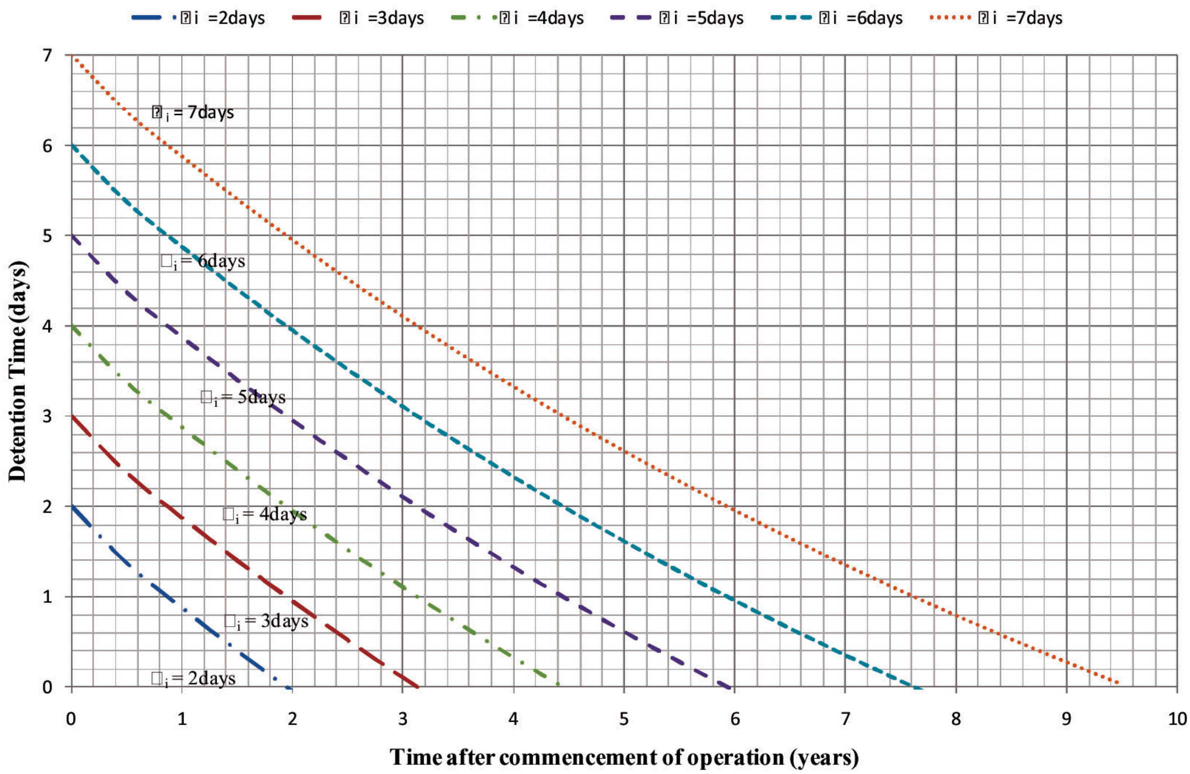

Figure 2: Decline of detention time for house connection, simple plumbing (typical wastewater flow = 0.064 m^3/day).

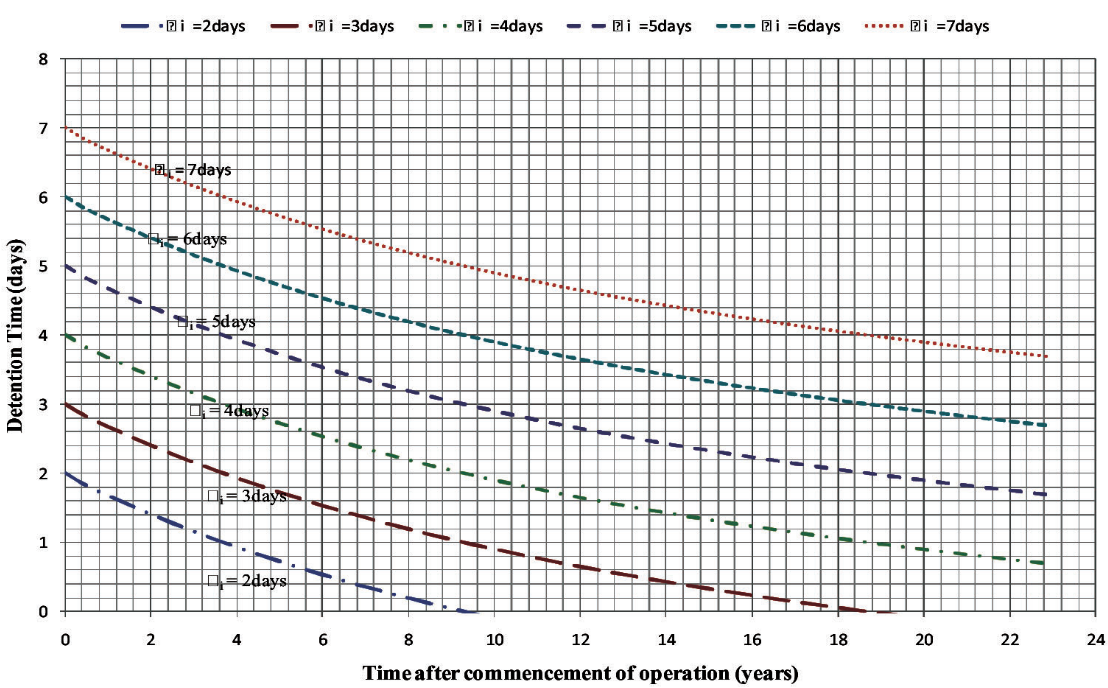

Figure 3: Decline of detention time for urban house with full water connection and garden (typical wastewater flow = 0.275 m^3/day).

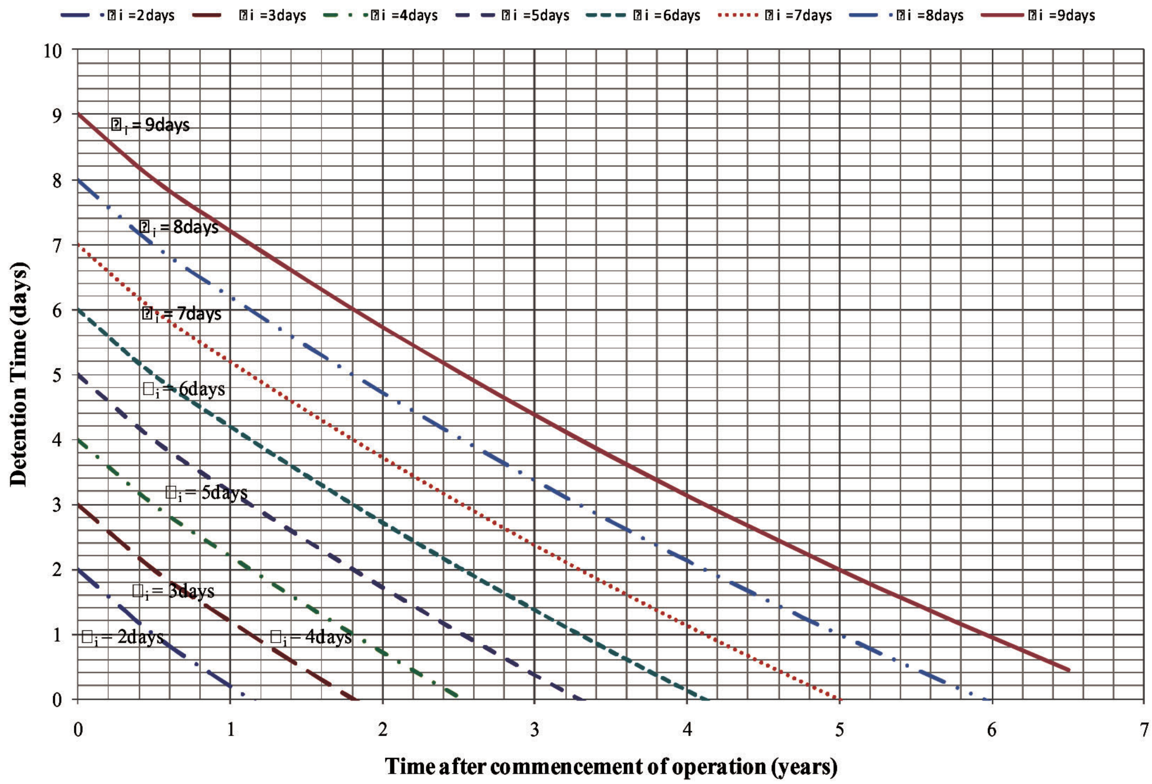

Figure 4: Decline of detention time for basic water requirement (typical wastewater flow = 0.04 m^3/day).

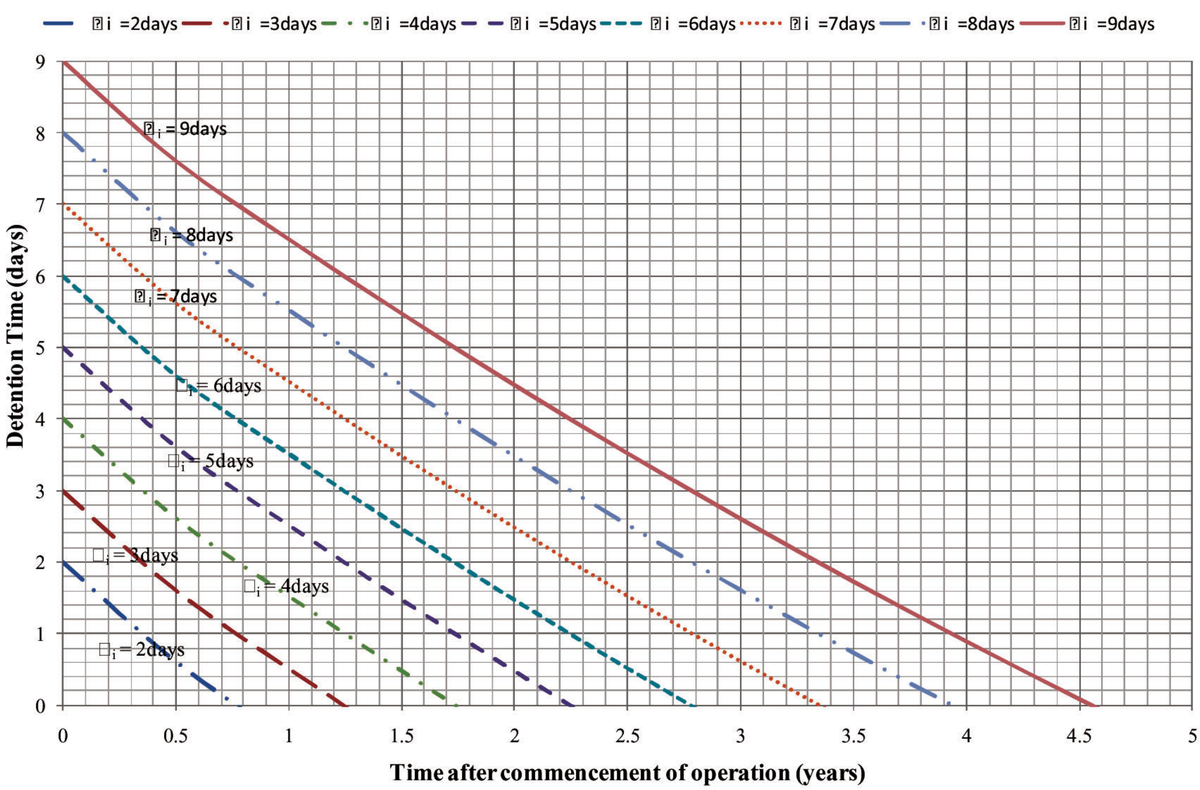

Figure 5: Decline of detention time for average Nigerian house (typical wastewater flow = 0.03 m^3/day).

detention time of three days can operate for nine years and still maintain the minimum 24 hours *residual detention time* introduced earlier. On the other hand, Figure 5 shows that for the average Nigerian water consumption, a septic tank sized for an initial detention time of three days for the same number of occupants will attain the minimum 24 hours *residual retention time* in only nine months and will, in fact, get filled up in less than one and half years. This explains why some people have frequent need to desludge their septic tanks while others have not had the need to desludge theirs for about a decade or more.

In most developing countries, septic tanks are rarely designed; rather, most contractors resort to arbitrary sizing. In Nigeria, for instance, the septic tank design specifications are given by the Public Works Department (PWD, 1943) as shown in Table 2. The specifications in this table are based on one day detention time and a wastewater flow of 0.114 m^3/capita/day. This specification is not realistic as a septic tank sized for an initial one day detention time will need desludging frequently. Furthermore, the wastewater flow of 0.114 m^3/capita/day is unrealistic (see Table 1).

Table 2: Schedule of septic tank sizing and dimensions (PWD, 1943)

Tank size	*Dimensions*				*No. of users*
	Length (m)	*Width (m)*	*Depth (m)*	*Capacity (m^3)*	
I	2.032	0.457	1.220	1.134	10
II	2.286	0.534	1.220	1.448	13
III	2.286	0.610	1.220	1.700	15
IV	2.540	0.686	1.220	2.125	18
V	3.048	0.762	1.220	2.832	25

The code recommended that a septic tank serving 10 people should have a dimension of 2.032 m (length), 0.457 m (width) and 1.22 m (depth) giving a total volume of 1.13 m^3. Even if the usual constant sludge accumulation rate of 0.04 m^3/capita/year (Winneberger, 1984) is assumed, in three years the tank will be overflowing with sludge (1.2 m^3). This implies that the tank will need desludging about every two years. Compare this with the recommendations of Crites and Tchobanoglous (1997). For instance, they recommended a tank of 2000 US gallons (7.57 m^3) for a four-bedroom house (Table 3). Obviously this is a very long shot from the meagre 1.13 m^3 recommended by PWD for a septic tank serving 10 people.

Table 3: Septic tank volumes (Crites and Tchobanoglous, 1997)

Number of bedrooms	*Tank capacity (US gallons)*	*Tank capacity (m^3)*
One or two bedrooms	1,000	3.785
Three bedrooms	1,500	5.678
Four bedrooms	2,000	7.570

The septic tank is not just meant for sewage treatment; it is also meant for sludge storage and decomposition. 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. Gary (1995) is of the opinion that increasing the desludging interval significantly reduces the volume of sludge produced, and so the operational cost of the unit to the owner. He further stated that longer sludge ages result in much more stabilized sludges which need not be disposed of to sewage treatment works. Of course longer storage periods will necessitate more volume and hence higher initial detention time. It has also been shown that since the septic tank is also a storage system, the detention time reduces as sludge accumulates.

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