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Rational design of septic tanks in warm climates

D. CEng, MICE, MIBiol, (Member),
neering, University of Leeds

BSc, MSc, DIC, PhD,
ficer, United Nations Centre for Human Settlements, Nairobi

INTRODUCTION

Septic tanks have been traditionally adopted in developing countries for use in high- and middle-income urban areas where housing densities are sufficiently low to accommodate some form of soil absorption system for on-site effluent disposal and where in-house piped water supplies are available. Their high capital cost and large plot area requirement have generally precluded their use in low-income areas. However, the use of septic tanks in conjunction with small-bore sewers has meant that this form of sanitation may be advantageously installed even in high-density, low-income areas (Sinnatamby, 1983; Otis and Mara, 1985).

The design of septic tanks in the tropics has tended to follow accepted practice in North America and Europe, and very little research has been undertaken into their performance in warm climates. Evidence does however indicate that the performance of septic tanks in warm climates differs considerably from their performance in temperate climates; and this has not yet been adequately reflected in their design. In this paper we present a design method for septic tanks which models the principal processes involved and which takes into consideration the effects of temperature and surge within the tank. Moreover septic tank research has hitherto been limited to individual systems serving single properties. In warm climates, however, the use of communal septic tanks serving groups of houses appears to have considerable advantages in relation to their costs, operation and maintenance and performance; these are also discussed.

SEPTIC TANK PERFORMANCE AND CURRENT DESIGN CRITERIA

Septic tanks in North America and Europe are most commonly designed to produce an effluent with little suspended matter likely to clog on-site disposal systems (Dardel, 1953). Consequently they have large retention times, usually of the order of 1 to 3 days. Since very little information is available on the performance of septic tanks in warm climates, similar criteria are often used by design engineers in warm climate countries. This leads to very conservative designs since the effects of temperature and surge (peak flow) attenuation in communal septic tanks are ignored. Pickford (1980) has suggested a comprehensive design method which takes into consideration the effect of temperature, but not the effect of reduced surges in septic tanks serving groups of houses.

Polprasert *et al.* (1982) summarized the average performance of septic tanks in temperate climates from data gathered by seven authors (Table 1). From these values and those presented by other authors (for example, Hickey and Duncan, 1966; Mann, 1979), the BOD_5 and SS removal efficiencies of septic tanks in temperature climates are most commonly within the range 25-45 and 50-70 per cent respectively, which are those usually achieved by plain sedimentation. However the BOD_5 and SS removals in anaerobic ponds in warm climates are in the range 60-80 per cent for both parameters (Arceivala *et al.*, 1970; Parker, Jones and Taylor, 1950; Mara and Silva, 1979; and Silva, 1982). Such high removal efficiencies indicate that, in addition to sedimentation, biodegradation is also occurring. The limited data available on the performance of communal septic tanks in hot climates indicate that their performance does in fact emulate that of anaerobic ponds. Phadke, Thacker and Deshpande (1972) observed BOD_5 and SS removal efficiencies both in excess of 80 per cent in a septic tank connected to two manually flushed water-seal latrines serving five families.

More recent work undertaken in north-east Brazil by de Oliveira (1982) on the performance of a communal septic tank found that overall retention times as low as 0.45 day were sufficient to remove on average 67 per cent of the influent BOD_5 and 78 per cent of the influent SS. On increasing the detention time to 0.75 day the BOD_5 removal efficiency increased only marginally to 70 per cent, although there was a small decrease in the average removal efficiency to 76 per cent. A two-compartment septic tank with an overall detention time of 0.75 day was observed to raise the BOD_5 and SS removal efficiencies to 72 and 82 per cent respectively. Although in the study by Phadke *et al.* (1972) there was a long retention time (20 days), the volumetric organic loadings in both these studies were of the same order, approximately 600 g BOD_5/m^3 day. Somewhat lower BOD_5 and SS removal efficiencies have been observed in individual septic tanks in hot climates. For example in Zambia, Vincent, Algie and Marais (1961) observed BOD_5 removal efficiencies of the order of 60 per cent in two-compartment septic tanks and 50 per cent in single-compartment tanks, and marginally lower BOD_5 removal efficiencies were observed by Choi (1978) and Oluwande, Sridhar and Okubadejo (1979). These observations no doubt reflect the greater influence of surge in individual systems.

The overall mean hydraulic retention time required in anaerobic systems depends to a large extent on the ambient temperature. Very low retention times have been successfully used in warm climates. Mara and Silva (1979) and Silva (1982) observed the performance of anaerobic ponds at 25-27°C with depths similar to those usually adopted in septic tanks for a range of retention times between 0.8 and 6.8 days, and concluded that there was little advantage in providing retention times greater than one day in anaerobic ponds. The reported BOD_5 and SS removal efficiencies were 76-80 and 74-82 per cent respectively. The marginal increase in performance brought about by increasing the retention time is also confirmed by work undertaken in India by Sharma and Lakshminarayana (1972) and Varandarajan *et al.* (1972). Vincent *et al.* (1961) observed no significant increase in BOD_5 removal at retention times in excess of two days. Many authors have stressed the need to provide greater retention times at lower ambient temperatures. Van Eck and Simpson (1966) found little reduction in BOD_5 in anaerobic ponds during the winter months when the temperature was below 10°C, but the reduction was 40-60 per cent at 20°C and over 80 per cent at 25°C and above. Parker *et al.* (1950) observed that ponds in Melbourne, Australia, with retention times during the summer of about 1.2

TABLE 1
Septic tank effluent concentrations and percentage removal
(Polprasert *et al.*, 1982)

Parameter	Concentration (mg/l, except as noted)	Percentage removal
pH (units)	7.1	—
Dissolved oxygen	0	—
Biochemical oxygen demand	160	27
Chemical oxygen demand	323	47
Total organic carbon	129	46
Total phosphorus	18	40
Phosphates	34	-240 (increase)
MBAS	7.6	67
Total solids	378	46
Total suspended solids	90	70
Total nitrogen	32	8
Ammonia nitrogen	27	-8 (increase)
Organic nitrogen	8	20
Nitrate nitrogen	0.14	(increase)
Nitrite nitrogen	0.061	(increase)
Chlorides	95	-111 (increase)
Alkalinity (as $CaCO_3$)	390	-225 (increase)
Total coliforms (/100ml)	10^5	ND
Faecal coliforms (/100ml)	10^5	ND

ND: no data

TABLE 2

Estimated effect of temperature on anaerobic treatment (McCarty, 1966)

Temperature (°C)	Rate of methane fermentation relative to that at 35°C	Retention time required for treatment relative to that at 35°C
5	0.1	10.0
15	0.4	2.5
25	0.8	1.2
35	1.0	1.0

days gave BOD_5 reductions of 65-80 per cent, but that during the winter months when the retention time was increased to 5 to 7 days the BOD reduction dropped to 45-60 per cent. Similar temperature-related increases in septic tank volumes were recommended by Alter (1969): temperatures in cold regions were said to require a volume twice as large as that required when wastewater temperatures were 12-15°C. This is no doubt a result of the fact that anaerobic digestion of organic matter is almost totally impaired at temperatures below 15° (Table 2), and hence the accumulation of solids within the tank becomes appreciable and must be accommodated by the provision of greater tank capacities. Hickey and Duncan (1966) and Oswald (1968) also observed that methane fermentation only occurred at temperatures of 15°C or above. Further evidence for this is provided by the characteristics of the settled sludge presented in Table 3: the higher percentages of volatile solids observed in the sludge in anaerobic systems at temperatures below 15°C indicate little stabilization.

TABLE 3

The effect of septic tank liquid temperature on sludge characteristics

Tank liquid temperature (°C)	Percentage volatile solids in sludge	Reference
0.6	79.0	Hickey and Duncan (1966)
4.4	77.4	Hickey and Duncan (1966)
15.0	74.6	Hickey and Duncan (1966)
26.0	52.7	de Oliveira (1983)
28.5*	37-47	Vasandarajan *et al.* (1972)

* anaerobic pond

All the above evidence suggests that septic tanks in hot climates should be designed with smaller overall retention times in such a way that they depart from their principal function as a sedimentation unit (as in temperate climates) to that of a biological reactor. Greater contact between the digesting sludge and the settleable, colloidal and dissolved nutrients in the influent sewage, brought about by the active seeding of the liquid layer with anaerobic organisms in the rising sludge particles (which results from the copious release of gas formed by the vigorous fermentation), will ensure higher BOD removal efficiencies and, with effective compartamentalization and a suitable outlet design, a greater efficiency in SS removal as well. In addition to the sedimentation of settleable solids, the seeding of the supernatant with active biomass will result in greater mineralization of the volatile fraction of the colloidal and dissolved nutrients and thus, besides reducing the supernatant BOD, make the particles more readily settleable. While the removal of SS in septic tanks in temperate climates is due almost exclusively to sedimentation, the mineralization of the volatile fraction (and consequently enhanced sedimentation) is likely to be a major mechanism for SS removal in hot climates. It is probably for this reason that Silva (1982) found only marginal improvements in SS removal in anaerobic ponds when their retention time was increased from 0.8 to 6.8 days, and why de Oliveira (1982) even observed a marginal decrease in the percentage removal of SS when the overall retention time was increased from 0.45 to 0.75 day.

The importance of the seeding mechanism in improving the effluent quality was demonstrated by Parker (1950) who, over a period of nine months, conducted experiments with two anaerobic ponds loaded identically. One pond was completely desludged at the beginning of the experiment, while the other contained 40 cm of sludge which had accumulated over the two preceding years of operation. The influence of the sludge layer on BOD_5 reduction is shown in Table 4. The consistently better BOD_5 removal achieved by the latter pond (until the difference became negligible due to sludge accumulation in the former) is clearly attributable to the enhanced seeding of its supernatant. A subsequent investigation into this phenomenon by Parker and Skerry (1968) confirmed Parker's (1950) original observation that greater contact between the sludge particles and the supernatant results in improved performance. Similar effects have been observed in septic tanks (Weibel, Straub and Thoman, 1949; Baumann and Babbitt, 1953). Clemesha (1907) reported that a

TABLE 4

Influence of sludge layer on BOD reduction in anaerobic ponds (Parker *et al.*, 1950)

Period	Influent BOD (mg/l)	BOD effluent (mg/l) Pond A*	BOD effluent (mg/l) Pond B*	BOD reduction (%) Pond A	BOD reduction (%) Pond B
9 April to 21 May	407	231	133	43.3	67.3
22 May to 17 September	407	291	254	28.4	38.5
18 September to 3 December	484	205	138	57.7	71.5
3 December to 24 December	448	157	145	65.0	67.5

* Pond A was completely desludged, but Pond B only partially desludged, prior to commencement of reporting period.

hanging scum board at the inlet, which obliged the influent sewage to come into contact with the sludge before passing to the second compartment, improved septic tank performance; again this was most probably due to better contact between the influent wastewater and the active sludge layer. While such a device could prove useful in tropical climates, its adoption in temperate climates would clearly have deleterious effects on performance, as observed by Stephenson (1968). However Silva (unpublished data, 1985) observed no difference in effluent quality between two anaerobic ponds which had the same retention time and temperature (25-27°C), even though one of them had twice the surface area of the other which was twice as deep.

The preceding review of the work of many authors shows that the performance of septic tanks in warm climates differs considerably from that in temperate climates. Clearly, further research is required to establish precise design parameters. Nevertheless, given the current state of knowledge, we believe that the design procedure given below, which is based on the design philosophy inherent in the Brazilian code (ABNT, 1982), represents a better approach to septic tank design in warm climates than hitherto available.

RATIONAL DESIGN OF SEPTIC TANKS

The Brazilian code considers the septic tank to comprise three zones, as follows:

(a) a sedimentation zone, for the settlement of settleable solids;
(b) a digestion zone, for the anaerobic digestion of the settled solids; and
(c) a storage zone, for the storage of digested solids.

To these should be added a fourth zone, for the storage of accumulated scum (Figure 1).

Sedimentation of settleable solids

As stated earlier, the settleable solids comprise two fractions: those in the tank influent, and those which rise up from the sludge layers through flotation by the gases produced therein. Although temperature affects the rate of sedimentation by changing the viscosity of the liquid phase, in practice its influence is minimal and may be ignored. Increases in temperature will, however, increase the rate of anaerobic digestion and hence result in greater gas production which would in turn resuspend more solids through flotation, and this enhanced seeding of the liquid phase with active anaerobic organisms makes the suspended matter, by the ensuing process of mineralization, more susceptible to settlement. This process usually attains equilibrium after 4 to 8 months of operation, but it can be adversely affected by shock loads and the resulting surges created within the tank.

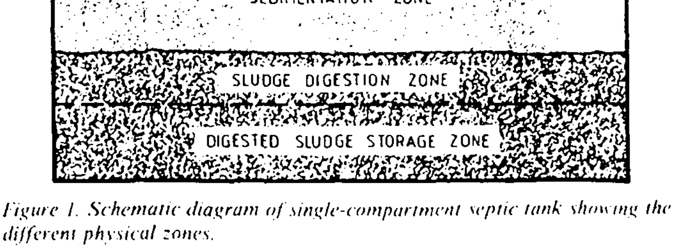

Figure 1. Schematic diagram of single-compartment septic tank showing the different physical zones.

TABLE 5
Recommended hydraulic retention times for sedimentation in septic tanks
(Hill and Ackers, 1953)

Population served	Hydraulic retention time (hours)
1- 5	48
5-25	24
25-50	18
>50	12

Research has shown that a two-hour hydraulic retention time at peak flow is sufficient under quiescent conditions for sedimentation of most of the settleable solids in raw sewage (IWPC, 1980). However, the higher hydraulic surges and consequent resuspension of settled solids experienced in a septic tank demand a greater hydraulic retention time for an equal removal of SS, and 24 to 48 hours have been suggested for use in Europe and the USA for septic tanks serving single households (Nicoll, 1974; EPA, 1980). However, peak discharges entering a septic tank decrease as the number of houses connected to it increases, largely because of the random nature in which plumbing fixtures in each house are used and the flow attenuation which occurs in the pipework. Hill and Ackers (1953) observed that, although the peak flow factor for a single house may reach 50 or more, for a cluster of houses it does not in general exceed 4 and rarely attains 6. Hence lower retention times may be employed in septic tanks serving groups of houses, and Hill and Ackers (1953) therefore recommended the hydraulic retention times shown in Table 5 to take account of sedimentation. Although many authors (for example, Doughty, 1979; Metcalf and Eddy Inc., 1979; and Nicoll, 1974) have acknowledged the possibility of reducing the retention time as the population served increases, few have suggested methods by which this may be incorporated into the design process. Fair and Geyer (1954) presented the following equation which does take this into account:

$$t_h = 1.5 - 0.3 \log (Pq) \qquad (1)$$

where t_h = minimum mean hydraulic retention time required for sedimentation, days
P = contributing population
q = wastewater flow, litres per caput per day (lcd)

The Brazilian septic tank code of practice (ABNT, 1982) recommends various minimum retention times depending upon the flow rate, as shown in Table 6. The methods of Hill and Ackers (1953), Fair and Geyer (1954) and ABNT (1982) for decreasing the retention time for settlement with increasing flows do show some variation, and therefore for general application the following are recommended:

(1) for septic tanks receiving both WC wastewater and sullage, retention times calculated from equation (1), subject to a minimum of 0.2 days; and
(2) for septic tanks receiving only WC wastewater a retention time calculated from the following equation, subject to a minimum of 1 day:

$$t_h = 2.5 - 0.3 \log (Pq) \qquad (2)$$

A minimum retention time is necessary in both cases in order to permit at least some effective seeding of the supernatant and to prevent washout of the active biomass. Equation (2) provides an extra day's retention time to allow for the much higher peak factors that occur with only WC wastewaters (de Kruijff, personal communication, 1986).

The corresponding septic tank capacity required for settlement (V_h, m^3) is given by:

$$V_h = 10^{-3} P q t_h \qquad (3)$$

TABLE 6
Recommended minimum retention times for sedimentation in septic tanks
(ABNT, 1982)

Flow (m^3/day)	Retention time (hours)
<6	24
6- 7	21
7- 8	19
8- 9	18
9-10	17
10-11	16
11-12	15
12-13	14
13-14	13
>14	12

Digestion of settled solids

Solids removed in the sedimentation zone pass to the sludge digestion zone where they are digested anaerobically. The characteristics and the quantity of fresh sludge produced vary from place to place. In general, however, it has been found to approximate 1 lcd. This figure is based on the production of 54 grams per caput per day of settleable solids, 39 grams being volatile with a relative density of 1 and 15 grams being fixed solids with a relative density of 2.5 and an overall moisture content of 95%, thus resulting in an overall volume of fresh sludge of 1.07 lcd (Fair and Geyer, 1954); it has since been confirmed by de Oliveira (1983) to be approximately true. Where more accurate estimates are available these should of course be used. Since the sludge in digestion decreases in volume during a given digestion time (t_d, days) from 1 lcd to zero (as the residue is now classified as digested sludge), the average quantity of sludge in the digestion zone is ($0.5 \times t_d$) litres per caput. Thus the volume required for the digestion of fresh sludge (V_d, m^3) is given by the expression:

$$V_d = 0.5 \times 10^{-3} P t_d \qquad (4)$$

Equation (4) assumes a linear relationship between the decrease in sludge volume and digestion time and, although this is not strictly true, designs based on this equation will be conservative. The relationship between temperature and the time required for digestion has been investigated by McCarty (1966), Fair, Geyer and Okun (1971), Gainey and Lord (1952) and de Morais (1977). Their data are presented graphically in Figure 2. Although there is some scatter, especially for retention times corresponding to temperatures lower than 15°C, this is mainly due to the definition of digestion assumed by the various authors. For example, the retention times quoted by Gainey and Lord (1952) are for complete digestion, while those quoted by Fair *et al.* (1971) are for the time taken to produce 90 per cent of the ultimate gas production. It is the former which is of interest in the present analysis. Despite these differences in definition, these authors' data give a very good correlation between temperature and the retention time required for digestion:

$$t_d = 1853 (T)^{-5/4} \qquad (5)$$

where T = temperature of the tank liquid, °C.

De Oliveira (1983) found that the average temperature within the septic tank was about equal to the average temperature of the influent sewage, but

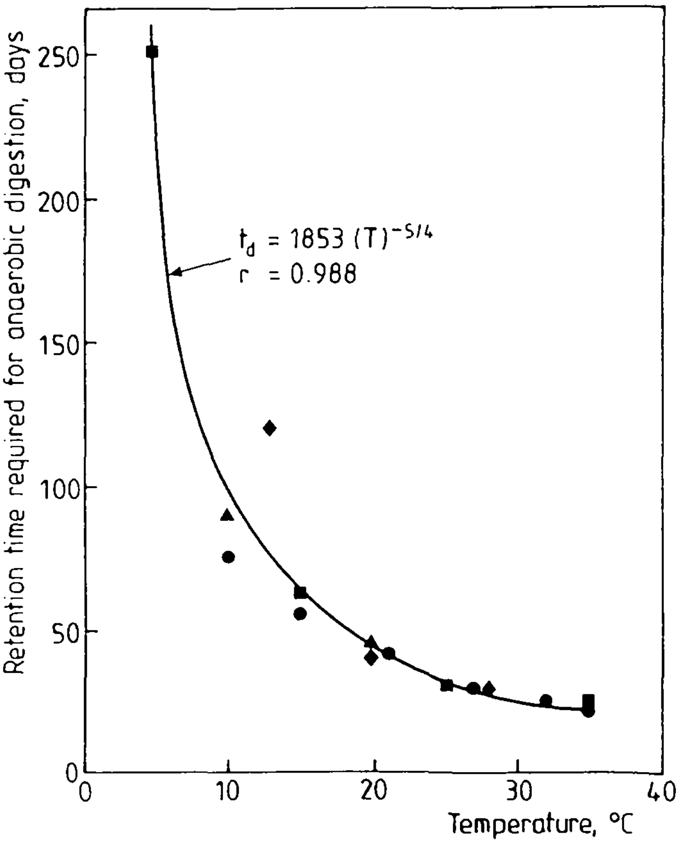

Figure 2. Sludge digestion times for various temperatures reported by McCarty (1966), ■; *Fair, Geyer and Okun (1971),* ●; *Gainey and Lord (1952),* ◆; *and de Morais (1977),* ▲.

Phadke *et al.* (1972) found it to be 1 to 2.5°C higher. Septic tank temperatures as low as 2.2°C have been recorded (Hickey and Duncan, 1966).

Alternatively an equation based on the process kinetics of a completely mixed biological reactor operated without cell recycle may be used to relate the minimum digestion time to temperature. Lawrence and McCarty (1969) stated that, when the influent substrate concentration is great enough not to be growth-limiting, the minimum mean cell residence time [$(\theta_c^T)_{lim}$, days] is approximately given by the equation:

$$(\theta_c^T)_{lim} = 1/(Yk_T) \tag{6}$$

where Y = true growth yield coefficient, mg VSS/mg BOD_5
k_T = maximum specific substrate utilization rate, day^{-1}

Lawrence (1971) found Y to be equal to 0.04 for high-lipid wastes, and O'Rourke (1968) defined the effects of temperature on methane fermentation over the temperature range 20-35°C by the following equation:

$$k_T = (6.67)10^{-0.015(35-T)} \tag{7}$$

Hence the minimum mean cell residence time is related to temperature as follows:

$$\theta_c^T = (6.67)10^{-0.015(35-T)} \tag{8}$$

Here θ_c^T represents the minimum mean cell residence time in days at a temperature T under ideal reactor conditions. However, for practical use this value must be increased by a factor of safety. Lawrence and McCarty (1969) suggested that the factor of safety should lie within the range 2 to 10. Metcalf and Eddy Inc. (1979) suggested a factor of safety of 2.5 for completely mixed continuous flow digesters. A large value is clearly necessary in septic tanks due to the poor control of conditions within the tank resulting from the fluctuating loading patterns and poor mixing. A factor of safety of 7.5 seems appropriate. Hence the minimum retention time required for sludge digestion (t_d, days) for the temperature range 20-35°C may be obtained from the equation:

$$t_d = 28(1.035)^{35-T} \tag{9}$$

Storage of digested sludge

Once the sludge is digested the residue settles to the bottom of the tank where it accumulates. Clearly the nature of the wastewater and its original solids content will determine the volume of the final residue produced. Since the total volume of sludge accumulated over a given period of time includes both the sludge in digestion and that already digested, the volume that must be provided in order to take account of the latter alone may be expressed as follows:

$$V_s = rPn \tag{10}$$

where V_s = volume required for storage of digested sludge, m^3
r = rate of accumulation of digested sludge and scum, m^3 per caput per year
n = desired interval between successive desludging operations, years.

A wide range of sludge accumulation rates is reported in the literature. Some of these are presented in Table 7. It is not usually clear how these values were obtained, whether they refer only to the volume of sludge or whether they include scum and, if so, whether the entire scum layer or only that portion below the water level is included. It is the volume of digested sludge and submerged scum which are of interest in the present context. Since no distinction has in the past been made between digested sludge and sludge in digestion, it is not unreasonable to presume that all the accumulations reported in Table 7 refer to both states of sludge.

From the characteristics of fresh and digested sludge it is possible to determine the proportion by which the volume of fresh sludge would decrease when digested. Fair and Geyer (1954) postulated that this reduction would approximate to a quarter of the original volume of fresh sludge. However, de Oliveira (1983) observed that the reduction factor was in fact of the order of 0.16. Assuming 1.0 litre of fresh sludge per caput per day, the corresponding rate of accumulation of digested sludge would be approximately 58 litres/caput/year. Although the Brazilian septic tank code (ABNT, 1982), based on Fair and Geyer's (1954) calculations, recommends that the rate of accumulation of digested sludge be considered as a quarter of the original volume of fresh sludge, not all of these solids will accumulate in the tank since some are removed in suspension in the tank effluent. In fact de Oliveira (1983) observed that the proportion of fresh sludge which, when digested, accumulates at the bottom of the septic tank was approximately 0.09 times its original volume. Once again assuming a daily per caput contribution of 1.0 litre of fresh sludge, the corresponding rate of accumulation of digested sludge would be 33 litres/caput/year. Brandes (1978a) observed that the rate of accumulation of sludge due exclusively to sullage was 8.3 litres/caput/year. Based on these observations and the long term rates reported in Table 7, the following rates of digested sludge accumulation are recommended for use in design:

WC wastewater and sullage:	40 litres/caput/year
WC wastewater only:	30 litres/caput/year

Similar sludge accumulation rates were suggested by Pickford (1980), who also recommended further increases when hard paper, sand and other similar materials are used for anal cleansing.

Besides the nature of the wastewater entering a septic tank, the two other principal factors which influence the rate of sludge accumulation within it are temperature and time. The effect time has on the overall rate of accumulation is exemplified by the data of Weibel *et al.* (1949) given in Table 7, which show that the rate of sludge accumulation decreased to less than half its original value after a time interval of only three years. In the past this phenomenon has been explained by suggesting that the sludge layers become compacted and hence denser as more digested sludge accumulates. While this is indeed one of the mechanisms responsible for the reduction in the rate of accumulation of sludge in septic tanks, its effect is only secondary to the influence that the volume of sludge in digestion has on the total volume of sludge within the septic tank (that is, the combined volumes of both digesting and digested sludge). Clearly during the first year of operation the overall rate of sludge accumulation is high since the volume of sludge in digestion constitutes a large proportion of the total sludge volume. The volume of sludge in digestion, as shown above, is a function of the temperature of the liquid within the septic tank; but this volume does not however change, irrespective of the number of years the septic tank has been in operation (assuming that the temperature remains constant).

However, the volume of digested sludge increases linearly with time (assuming a constant rate of digested sludge accumulation). Thus the total volume of sludge in the tank increases with time as shown in Figure 3. The importance of the temperature and the time over which the sludge accumulates, and the corresponding effect of the volume of the sludge in digestion over the total sludge volume, is clearly demonstrated in Table 8. Since the volume of sludge in digestion in a septic tank is greater for lower temperatures than for higher temperatures, the overall rate of sludge

TABLE 7

Reported rates of sludge accumulation in septic tanks

Reference	Sludge accumulation rate (litres/caput/year)	Accumulation period (years)
Weibel *et al.* (1949)	93	1
	60	2
	43	4
	39	6
	38	8
	38	10
Hill and Ackers (1953)	96	1
Vincent *et al.* (1961)	28-40*	—
Brandes (1978b)	80	2
Egbuniwe (1980)	30-60	—

* WC wastewaters only

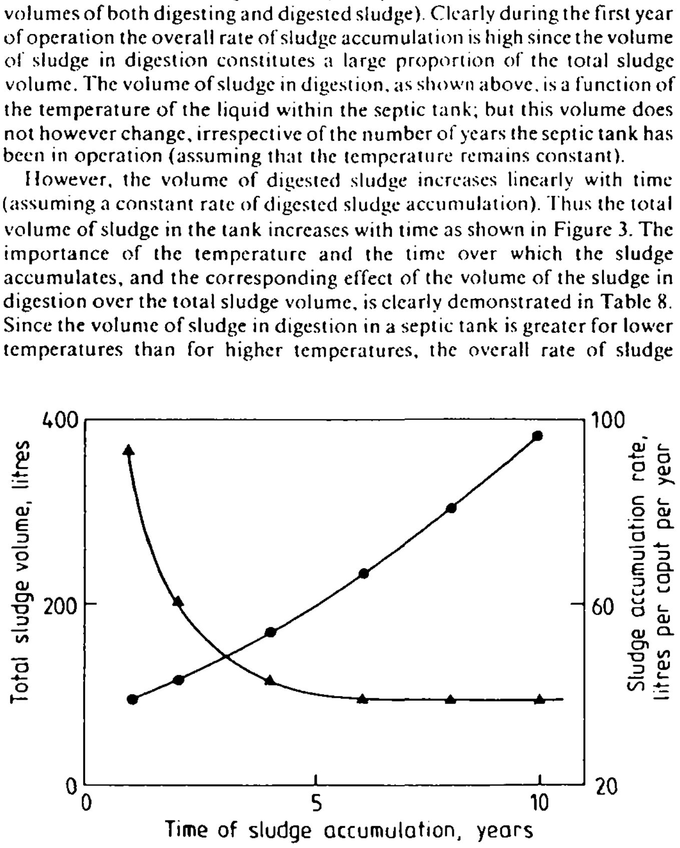

Figure 3. Variation in sludge volume (●) and sludge accumulation rate (▲) with time (data of Weibel et al. *(1949) given in Table 7).*

TABLE 8
Effect of time and temperature on sludge accumulation rates

	Temperature					
	10°C			25°C		
Number of years of operation	Vol. of sludge in digestion (l/cap)*	Vol. of digested sludge (l/cap)**	Rate of total sludge accumulation (l/cap.yr)	Vol. of sludge in digestion (l/cap)*	Vol. of digested sludge (l/cap)**	Rate of total sludge accumulation (l/cap.yr)
1	52	29	81	17	36	53
2	52	69	60	17	76	47
4	52	149	50	17	156	43
6	52	229	47	17	236	42
8	52	361	45	17	316	42
10	52	441	44	17	396	41

* from Equations (3) and (4)
** from Equations (9) and (4) and assuming a digested sludge accumulation rate of 40 l/cap.yr.

accumulation is naturally higher in temperate climates than in tropical climates. However, if the temperature is suddenly increased, the volume of sludge in digestion would decrease and so would the overall rate of sludge accumulation. This explains Laak's (1980) observation that the sludge-clear space (depth of supernatant) in a septic tank increased by 40 per cent during the summer, and underlines the secondary nature of the effect of sludge compaction as a mechanism for reducing sludge accumulation rates with time. It further highlights the limitation of applying temperate climate data and practices to tropical conditions. For example, the sludge accumulation rate data of Weibel *et al.* (1949) have been incorporated in the guidelines for the use of septic tanks in South Africa (Malan, 1964), which (unless similar temperatures are experienced within the septic tank) will result in overdesign.

Most codes of practice suggest fixed rates of sludge accumulation which are very conservative and, more importantly, not related to the number of years of operation: for example, 90 litres/caput/year in the UK (BSI, 1983) and 77 litres/caput/year in India (ISI, 1969). By considering the volumes required for digesting sludge and digested sludge separately, as proposed here, the effects of temperature and time on the volume of accumulated sludge are automatically taken into account at the design stage.

Overall design capacity

The overall design capacity of the septic tank (V, m^3) is the sum of the volumes required for sedimentation, digestion and storage of digested sludge and is thus given by the following expression:

$$V = V_h + V_d + V_s \quad (11)$$

FACILITIES DESIGN

Malan (1964) indicated that the shape of the tank is relatively unimportant. However, rectangular tanks have been observed to perform more satisfactorily than square (Shelty, 1971) and cylindrical tanks (Choi, 1978). Often a rectangular tank with a length to breadth ratio of 3 to 1 and a depth between 1.0 and 2.25 m is recommended. Hill and Ackers (1953) recommended that two compartments be provided to improve performance and that the first compartment should be twice the capacity of the second. Since then many authors (including Laak, 1980; de Oliveira, 1983) have reiterated the importance of compartmentalization. This was however questioned by Seabloom, Carlson and Engeset (1983), who reported that single-compartment septic tanks gave consistently better BOD and SS removal. However these authors did not give any details about the inter-compartmental overflow arrangement used and whether or not baffles were provided. These two items may in fact be more important than whether the tank is compartmentalized or not.

Ideally all septic tanks should possess inlet and outlet T-junctions extending to a depth below the water level corresponding to 200 mm above the maximum sludge depth, and extending 150 mm above the water level. The outlet tee should be inclined at 60° to the vertical (by rotating it about its horizontal axis); two such tees are recommended for communal septic tanks. The use of inclined overflow tubes in such a way that they function as lamella settling tubes to improve SS removal has been suggested by Willson, Reed and Newman (1975), Cynamon (1980), and Laak (1980). The invert of the outlet pipe should be between 50-75 mm below the invert of the inlet pipe. The use of weirs over the entire width of the septic tank has been suggested by some authors (BSI, 1983; Malan, 1964; Pickford, 1980), especially for large tanks; but the inclined T-junction referred to above provides better surge attenuation characteristics since a given inflow volume creates a greater rise in water depth and a slower discharge rate. Gas deflectors placed under the entrance to the overflow pipe have also been reported to improve the performance of septic tanks; details of these are given in EPA (1980) and Malan (1964).

DISCUSSION

The use of septic tanks in low-income, high-density areas in developing countries has many limitations. Firstly, they are a high-cost sanitation technology. Many authors (Holland, 1977; Kalbermatten, Julius and Gunnerson, 1982; Cotteral and Norris, 1969; Bradley, 1983) have reported septic tanks to be as expensive as (and often even more costly than) conventional sewerage. This is especially true for high-density areas with soils of low permeability. The use of this form of sanitation in developing countries has further limitations in that it occupies a considerable amount of the compound area, and where the soil is insufficiently permeable it is common to see undesludged septic tanks and overloaded soakaways connected to, or overflowing into, the nearest surface drain (Bradley, 1983), thus posing severe environmental and health hazards. The breeding of culicine mosquitoes (which are the vector of Bancroftian filariasis in many parts of the world) has also been observed in badly constructed septic tanks (Goettel, Toohey and Pillai, 1980).

Secondly, septic tanks and soakaway systems are usually considered to be limited to low-density urban areas, typically <100 persons per hectare, although the use of a three-compartment tank where the first two are used in series for WC wastewaters which overflow to the third compartment which also receives sullage, has been speculated to be suitable for medium-density areas of about 200 persons per hectare (Kalbermatten *et al.*, 1982). However, their application in high-density urban areas is limited. In such areas the use of small-bore sewers is often recommended (Otis and Mara, 1985), but it is important to ensure that the septic tanks be desludged and maintained regularly, which is a task best undertaken by the local sewerage authority; Fey and Crane (1978) have reported on the need to institutionalize individually owned septic tanks even in Wisconsin, USA, in order to ensure their proper maintenance.

Cynamon (1980), in an attempt to overcome the problems associated with desludging septic tanks, suggested the use of an adjacent sludge drying bed connected to the bottom of the septic tank by means of a flexible plastic pipe which may be lowered to drain the sludge which, after drying for at least a year, may be removed with no health risk (Figure 4). Cynamon also suggested the use of thin (50 mm) precast concrete units in order to reduce the overall cost of the system. While such a system obviates the main disadvantages of this form of sanitation, namely that of high cost and frequent mechanical desludging, it has still to be evaluated in the field. Further, the removal of scum is still likely to require handling of the tank contents which is precisely what the provision of an attached sludge drying bed was intended to obviate.

A cheaper and often more practical alternative is to use communal septic tanks to serve groups of houses, especially in high-density areas (>500 persons per hectare) with small-bore sewers to receive the tank effluent. Communal septic tanks serving as many as 500 persons have been recommended (Impey, 1959), although a maximum number of 300 persons is more usual. The large decrease in the per caput investment cost of septic tanks with increasing number of persons served as observed in north-east Brazil (Sinnatamby, 1983) is shown in Figure 5; a similar relationship has been observed by the authors in southern Pakistan. Communal septic tanks have the added benefit of easier institutional control and maintenance, since

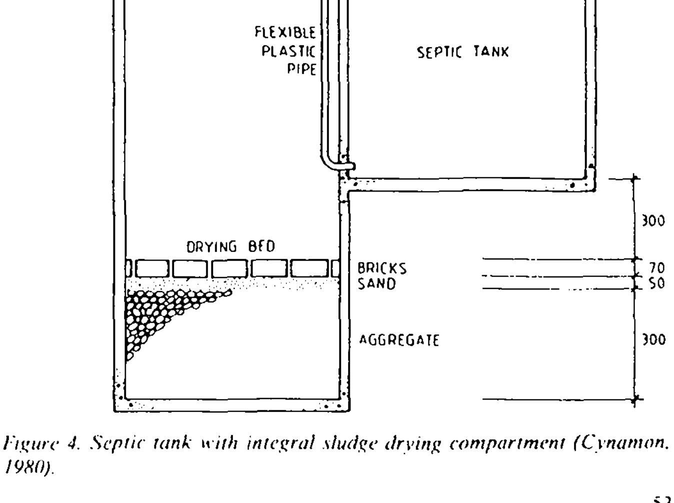

Figure 4. Septic tank with integral sludge drying compartment (Cynamon, 1980).

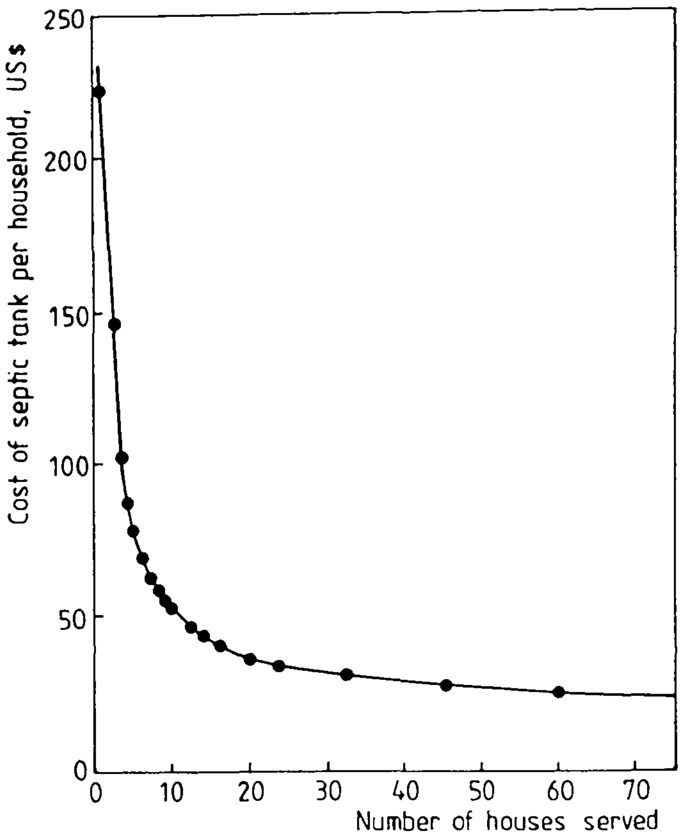

Figure 5. Variation in per household septic tank costs with number of households served (data from the city of Natal, north-east Brazil).

their numbers in a given area are few and they can be located where access is convenient for large vacuum tankers. The limited data available on their performance appear to suggest that it is superior to that of small septic tanks serving single households. These advantages of communal septic tanks have not been well appreciated in the past since most design methods have been orientated, implicitly or explicitly, towards the use of individual septic tanks.

Table 9 illustrates the decrease in the per household volume of septic tanks brought about by increasing the number of houses connected to it, using the rational design method; the volumes given by the design procedures of Pickford (1980) and Kalbermatten *et al.* (1982) are also included for comparison. It is evident that, while all designs give approximately the same volume for a single household, very much larger volumes are obtained for communal tanks by the latter procedures than by the rational design procedure. This is mainly due to the fact that they do not make adequate allowance for the reduced surges in communal septic tanks.

Hitherto communal septic tanks have invariably been built entirely of reinforced concrete. However, brickwork with concrete columns (to divide large spans) and nominal reinforcement (3 mm diameter) placed within the mortar at suitable spacings in the brick courses constitutes a much cheaper alternative to reinforced concrete walls.

CONCLUDING COMMENTS

Despite the large amount of literature on the subject of septic tanks, comparatively little is known about their performance in hot climates. Attempts to extend temperate climate practice to hot climates have serious limitations and are not always prudent, since the performance and mode of operation of septic tanks in hot climates differ considerably from those in temperate climates. The rational method of design suggested herein attempts to take account of these differences. The effects of increased temperature, and consequently of increased seeding of the supernatant with active biomass, improve septic tank performance in hot climates. The reduced effect of surges in communal septic tanks also improves performance, so that they require a smaller per household volume and are consequently more cost-effective. Communal septic tanks have the added advantage of being able to be located in areas of convenient access for desludging.

TABLE 9

Comparison of septic tank designs*

No. of houses served	Septic tank volume (m^3)		
	Rational method	Pickford (1980)	Kalbermatten *et al.* (1982)
1	0.76	0.76	0.70
5	2.62	3.80	3.50
10	4.77	7.60	7.00
20	8.64	15.20	14.00
40	15.47	30.40	28.00
60	21.91	45.60	42.00

* Assumptions: wastewater flow, 100 lcd; household size, 5; temperature, 20°C; desludging frequency, once per year; digested sludge accumulation rate, 40 l/cap yr.

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