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MODELING OF SEEPAGE LOSSES IN SEWAGE SLUDGE DRYING BED

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ABSTRACT
This research was carried out to develop a model governing seepage losses in sewage sludge drying bed. The model will assist in the design of sludge drying beds for effective management of wastes derived from households' septic systems. In the experiment conducted this study, 125kg of sewage sludge, 90.7% moisture content was thoroughly mixed and intermittently into a sand drying bed of dimensions 1.0m length, 0.3m width, 0.8m depth including overboard and having a 50mm diameter drain pipe. Seepage were measured at 24 hours intervals for 15 days, after which seepage model was derived from first principles based on the concept that seepage is inversely proportional to time. The model is in the form $q_s = a + be^{k_1 t}$ and for this model, two cases exist, cases I and II respectively. For case I, as time, t tends to infinity (i.e. $t \rightarrow \infty$) at which point seepage has completely stopped (i.e $q_s=0$) and the seepage curve intercepts the x-axis so that the intercept a = 0, data generated was modeled first by calibration using odd number values of seepage corresponding to 1 to 15 days. Coefficient of correlation after calibration was found to be r=-0.8474, and after verification using even number values of seepage corresponding to 2 to 14days, r =0.8474 was the coefficient of correlation between measured and calculated quantities of seepage which validates the model. For seepage model case II, this was at the initial stage of application of sludge into the drying bed at which point seepage was still taking place so that the intercept $'a' \neq 0$, then 'a' was determined by trial and error. Again, calibration and verification was done as in case I and correlation of measured and calculated seepage gave r=0.972, this high value of 'r' validates the model.

Key words: *seepage losses, sewage sludge, drying bed*

1. INTRODUCTION
Sludge dewatering is a physical unit process used to remove as much water as possible from sludge to produce a highly concentrated cake, and is dried naturally by a combination of seepage and evaporation. The rational equation for drying is dependent on time for sludge to drain (t_1) (i.e. the time during which draining is the primary drying mechanism) and time (t_2) for moisture to evaporate from the drained sludge [1]. Raw sludge is watery, containing only 2% solids. Hence, water removal is very necessary in order to reduce its volume, facilitate handling and reduce its size for downstream unit. This is achieved through thickening by gravity or air floatation [2]. Sludge, which is produced as a by-product of all treatment processes, has considerable potential as a fertilizer and soil conditioner. The liquid sludge which contains 90-98% water can be partially dewatered by a number of processes. It is important to note that dewatering and disposal of waste sludge is a major economical consideration in the operation of wastewater treatment plants. Sludge drying beds are the oldest method of sludge dewatering and are still used extensively in small to medium sized plants to dewater sludge [3]. They are relatively inexpensive and provide dry sludge cake. In the recent years, much advancement has been made to the conventional drying beds and new systems are used on medium and large sized plants. Conventional sand beds consist of a layer of coarse sand 15-25cm in depth and supported on a gravel bed (0.3-2.5cm) that incorporates selected tiles or perforated pipe under-drain. Sludge is placed on the bed in 20-30cm layers and allowed to dry. Sludge cake removal is manual by shoveling into wheelbarrows or trucks or a scraper or front-end loader. The drying period is 10-15 days and the moisture content of the cake is 60-70%.

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Nevertheless, dewatering of the different types of water from sludge was studied by several investigators such as [4-8]. The sludge for land application must meet risk-based pollutants limit to protect public health and the environment [9]. It has often been observed, that the presence of dispersed particles is due to physical, chemical or biological processes [10]. Drying beds are not adapted for regions with heavy rain falls and frequent flooding or where the water table is high. In any case, the ponds should be sealed to prevent infiltration of the pathogen containing percolate and a counter bund can prevent runoff to flow in. According to [11], bio-solids must meet class B requirements before disposal to the agricultural lands. The implicit goal of class B requirements is to reduce pathogens in sewage sludge to levels that are unlikely to pose a threat to public health and the environment [11]. The term sludge is a study in diversity and sludge result from various anthropogenic activities. Because of that each type of sludge has specific problem that must be evaluated in order to determine treatment feasibility [12].

For instance, current technologies for oil contaminated soil are used to remediate oil sludge. These techniques include ultrasound, solidification, pyrolysis, incineration, chemical treatments, heat cleaning and extraction [13 – 17]. Application of sewage sludge is the most significant source of anionic surfactants (ASs) in the terrestrial environments, anionic surfactants being amphipatic compounds consisting of a hydrophobic and hydrophilic part. [18]. The main problem in treating urban wastewaters is basically reduced to finding an environmentally correct technology at the lowest cost [19].

2. MATERIALS AND METHOD

2.1 Experimental Set-up for Seepage Experiment

2.0155g sludge sample was oven dried at 105 ^0C, to enable determine the initial water content of the sludge. This was carried out in accordance to [20]. Result showed that moisture content was 81.01%. Further to that, 60.95kg of sludge containing 49.37kg of water based on 81.01% water content was weighed and placed inside a container, 64.05kg of water was added to the sludge so that the water content increased from 81.01% to 90.74%. The contents were thoroughly mixed to a uniform consistency before application into the drying bed.

The drying bed is a simple sand and gravel filters on which batch loads of sludge are dewatered. Generally, the gravel layer (grain diameter of 7 – 15mm) of 20cm thick was used, and this is followed by a final sand layer 20cm thick, (grain diameter of 0.2 – 0.6mm). The dimensions of the prototype model (i.e. the drying bed) is 100cm long, 30cm wide, 70cm deep. The drain pipe is 50cm diameter and the length extending into the bed is perforated so that filtration can take place. Sludge were applied on the bed intermittently and the percolate collected at 24 hours interval for 15 days. Table 1 below shows the results from seepage experiment.

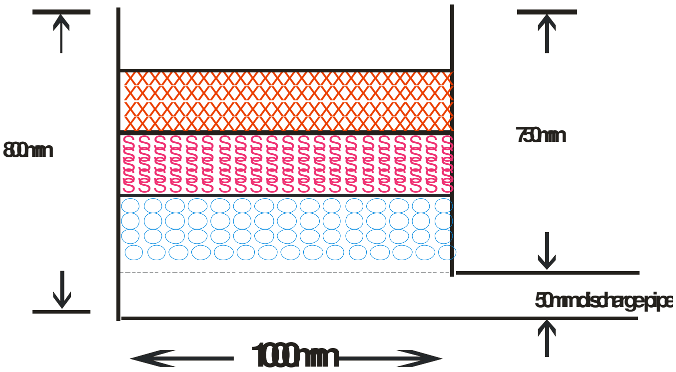

Figure 1: Longitudinal view of drying bed

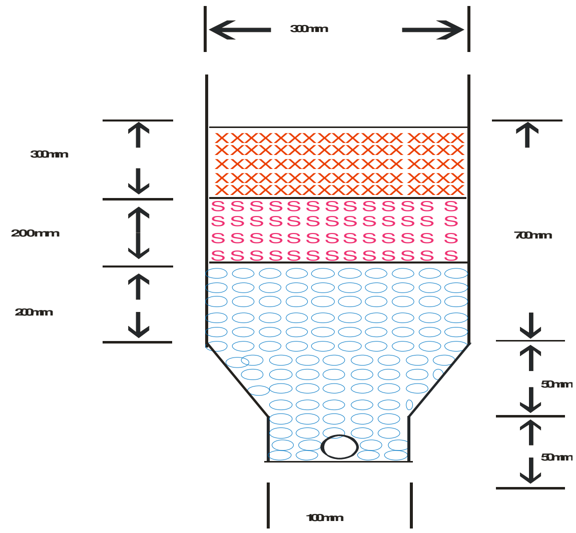

Figure 2: Cross-sectional view of drying bed

3. MATHEMATICAL DERIVATIONS

3.1 Derivation of Seepage Model

Assumption: Moisture contents of the sewage sludge, gravel and sand layers vary as quantity of water in sludge decrease with time. But for ease of modeling, moisture contents in these media are assumed to be constant at any instantaneous time.

Table 1 : Table of variation of instantaneous and cumulative seepage with time

Time(days)	Seepage, S (m^3) $\times 10^{-3}$	Cumulative seepage, CS (m^3) $\times 10^{-3}$	ln (t)	ln(CS)
1	19641	19641	0	-3.9301
2	10936	30577	0.6931	-3.4875
3	6823	37400	1.0990	-3.2861
4	4087	41487	1.3863	-3.1824
5	2779	44266	1.6094	-3.1175
6	2557	46823	1.7918	-3.0614
7	2539	49362	1.9459	-3.0086
8	2312	51674	2.0794	-2.9628
9	2192	53866	2.1972	-2.9213
10	2121	55987	2.3026	-2.8826
11	2067	58054	2.3979	-2.8464
12	2011	60065	2.4849	-2.8123
13	1933	61998	2.5649	-2.7807
14	1878	65658	2.6391	-2.7233
15	1850	67569	2.7081	-2.6946

Seepage decreases with time. This implies that the rate at which seepage is taking place from the sludge is inversely proportional to time. Therefore , the equation is expressed as;

$$\frac{dq_s}{dt} = -k_1 q_s + k_2 \quad (1)$$

The constant k_1 accounts for slope of the seepage curve when flow is very high (i.e. the initial stage of application of sludge into the drying bed and k_2 accounts for the slope of the seepage curve when flow is very low (i.e. when the curve is nearly asymptote with the x-axis) prior to stoppage of flow at which point the curve finally touches the x-axis.

The integrating factor in Equation (1) is $(I.F.) = e^{k_1 t}$

Multiplying Equation (1) by the integrating factor,

$$e^{k_1 t}\frac{dq_s}{dt} + k_1 e^{k_1 t} q_s = k_2 e^{k_1 t} \quad (2)$$

$$\left[q_s e^{k_1 t}\right]^1 = k_2 e^{k_1 t} \quad (3)$$

$$q_s = e^{-k_1 t}\left[\int k_2 e^{k_1 t} dt + c\right] = e^{-k_1 t}\left[\frac{k_2}{k_1} e^{k_1 t} + e^{-k_1 t} c\right] \quad (4)$$

$$\Rightarrow q_s = \frac{k_2}{k_1} + e^{-k_1 t} c \quad (5)$$

At $t = 0,\ q_0 = q_s$

$$\therefore c = q_0 - \frac{k_2}{k_1} \quad (6)$$

Substituting $q_0 - \frac{k_2}{k_1}$ in Equation (5) we have

$$\therefore q_s = \frac{k_2}{k_1} + \left(q_0 - \frac{k_2}{k_1}\right) e^{-k_1 t} \quad (7)$$

Substituting a for $\frac{k_2}{k_1}$ and b for $\left(q_0 - \frac{k_2}{k_1}\right)$ in Equation (7), we have

$$q_s = a + b e^{-k_1 t} \quad (8)$$

Equation (8) is the general equation governing seepage losses in sewage sludge drying bed and will serve as seepage model case II in the analysis.

Two Cases Exist

Case I

If time $t \to \infty$, or is very large, then seepage will stop.

$\Rightarrow q_s = 0$, and substituting in Equation (8) we have

$0 = a + b e^{-\infty}$, so that $a = 0$

and if $a = 0$, then

$$q_s = b e^{-k_1 t} \quad (9)$$

Equation (9) is for instantaneous losses due to seepage in drying bed for case I. To determine the total losses , we integrate Equation (9) between the limits $t = 0$ to $t = T$, so that Equation (9) becomes;

$$\int_{t=0}^{t=T} q_s dt = -\frac{b e^{-k_1 t}}{k_1} \quad (10)$$

Between the limits $t = 0$ and $t = T$, we have

$$\frac{-b e^{-k_1 T}}{k_1} - \left(-\frac{b e^{-k_1 (0)}}{k_1}\right)$$

$$q_s = \frac{b}{k_1} - \frac{b e^{-k_1 T}}{k_1} \quad (11)$$

Where;

$q_s =$ Total seepage over a given period;

$b = \left(q_0 - \frac{k_2}{k_1}\right)$, which is the slope of the function $q_s = a + b e^{-k_1 t}$;

$k_1 =$ The rate constant; and

$T =$ time

Linearizing Equation (9), we have

$$\ln q_s = \ln b - k_1 t \quad (12)$$

Case II

Equation (8) is for instantaneous losses due to seepage in drying bed for case II (General seepage losses equation). To determine the total losses , we integrate Equation (8) between the limits $t=0$ to $t=T$, so that Equation (8) becomes;

$$\int_{t=0}^{t=T} q_s dt = at + \frac{be^{-k_1 t}}{-k_1} \quad (13)$$

Between the limits $t=0$ and $t=T$, we have

$$q_s = aT + b\left(\frac{e^{-k_1 T}}{k_1} - \frac{1}{k_1}\right) \quad (14)$$

4. RESULTS AND DISCUSSION

Regressing seepage q_s on time, t and determining the coefficient of correlation $'r'$ using the expression below we have;

$$r = \frac{n\sum t.\ln q_s - \sum t.\sum \ln q_s}{\left[n\sum t^2 - \sum (t)^2\right]^{\frac{1}{2}}\left[n\sum \ln q_s^{\,2} - (\ln q_s)^2\right]^{\frac{1}{2}}}$$

The slope k_1 was computed using the expression;

$$k_1 = \frac{n\sum t.\ln q_s - \sum t.\sum \ln q_s}{\sqrt{n\sum t^2 - \sum (t)^2}}$$

Where, q_s is seepage from the drying bed; and

n is the number of data involved.

Therefore,

$$r = \frac{8(200.5846) - 64(28.0578)}{\left[8\times 680 - 64^2\right]^{\frac{1}{2}}\left[8\times 103.2186 - 28.0578^2\right]^{\frac{1}{2}}} = -0.84$$

and,

$$k_1 = \frac{8(200.5846) - 64(28.0578)}{\sqrt{8(680) - 64^2}} = -0.14213$$

Substituting -0.14213 for k_1 in Equation (12), it becomes

$$\ln \bar{q}_s = \ln b - 0.14213\bar{t}$$

$$\frac{28.0578}{8} = \ln b - 0.14213\left(\frac{64}{8}\right)$$

$$\ln b = \frac{28.0578}{8} + 0.14213\left(\frac{64}{8}\right) = 4.64427$$

$$\therefore b = e^{4.64427}$$

$$\Rightarrow b = 103.9869$$

Table 2: Calibration of seepage model for case I

Seepage $q_s(m^3) \times 10^{-1}$	$t(days)$	$\ln q_s$	t^2	$\ln q_s^{\,2}$	$t.\ln q_s$
196.41	1	5.2802	1	27.8805	5.2802
68.23	3	4.2229	9	17.8329	12.6687
27.79	5	3.3247	25	11.0536	16.6235
25.39	7	3.2344	49	10.4613	22.6408
21.92	9	3.0874	81	9.5320	27.7866
20.67	11	3.0287	121	9.1730	33.3157
19.33	13	2.9617	169	8.7717	38.5021
18.50	15	2.9178	225	8.5136	43.7670

$\sum t = 64$ $\sum \ln q_s = 28.0578$ $\sum t^2 = 680$ $\sum \ln q_s^{\,2} = 103.2186$
$\sum t.\ln q_s = 200.5846$

Therefore, the model for seepage model case I can be represented in two forms (linear and exponential) as shown below;

$$\ln q_s = 4.64427 - 0.14213t \quad (15)$$

and

$$q_s = 103.9869e^{-0.14213t} \quad (16)$$

For case I, verification was done using Equations (15) and (16)

Let $\ln q_{sm}$ = measured $\ln q_s$ and $\ln q_{sc}$ = calculated $\ln q_s$

Correlation between q_s - measured and q_s - calculated.

$$r = \frac{7(85.346) - 23.7757(24.5507)}{\sqrt{7(83.1164) - 24.5507^2}\times\sqrt{7(88.3679) - 24.5507^2}} = 0.8474$$

Table 3: Verification of seepage model case I when ($\ln q_s = 4.64427 - 0.14213t$)

$t(days)$	q_s	$\ln q_{sm}$	$\ln q_{sc}$	$\ln q_{sm}^{\,2}$	$\ln q_{sc}^{\,2}$	$\ln q_{sm}.\ln q_{sc}$
2	109.36	4.6947	4.3600	22.0402	19.0096	20.4689
4	40.87	3.7104	4.0758	13.7671	16.6121	15.1228
6	25.57	3.2414	3.7915	10.5067	14.3755	12.2898
8	23.12	3.1407	3.5072	9.8640	12.3005	11.0151
10	21.21	3.0545	3.2230	9.3299	10.3877	9.8447
12	20.11	3.0012	2.9387	9.0072	8.6360	8.8196
14	18.78	2.9328	2.6545	8.6013	7.0464	7.7851

$\sum \ln q_{sm} = 23.7757$ $\sum \ln q_{sc} = 24.5507$ $\sum \ln q_{sm}^{\,2} = 83.1164$ $\sum \ln q_{sc}^{\,2} = 88.3679$ $\sum \ln q_{sm}.\ln q_{sc} = 85.346$

$\ln q_s$ (Measured) $= a_1 + b_1 \ln q_s$ (Calculated)

$$b_1 = \frac{7(85.346) - 23.7757(24.5507)}{7(83.1164) - 24.5507^2} = 0.8295$$

$$a_1 = \sum \bar{q}_{sm} - b_1 \bar{q}_{sc} = \frac{23.7757}{7} - 0.8295\left(\frac{24.5507}{7}\right) = 0.4874$$

$$\therefore \ln q_{sm} = 0.4874 + 0.8295 \ln q_{sc} \quad (17)$$

Equation (17) is the relationship between measured and calculated seepage in sewage sludge drying bed.D

4.1 Seepage Model

4.1.1 Case I (exponential form)

Let $x = q_s$ (measured) and $y = q_s$ (calculated). Note that q_s (calculated) is $q_s = be^{-k_1 t}$. This implies that the values 'y' in the second column of Table 4 were derived from $q_s = be^{-k_1 t}$.

Table 4: Verification of seepage model case I when $q_s = be^{-k_1 t}$

x	y	x^2	y^2	xy
109.36	78.26	11312.45	6124.63	8558.51
40.87	58.89	1670.36	3468.03	2406.83
25.57	44.32	653.82	1964.26	1133.26
23.12	33.36	534.53	1112.89	771.28
21.21	25.10	449.86	630.01	532.37
20.11	18.89	404.41	356.83	379.88
18.78	14.22	352.69	202.21	267.05

$\sum x = 259.02$ $\sum y = 273.04$ $\sum x^2 = 15378.12$ $\sum y^2 = 13858.86$

$\sum xy = 14049.18$

$$r = \frac{n\sum xy - \sum x \sum y}{\left[\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^2}\right]\left[\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}\right]}$$

$$r = \frac{(7 \times 14049.18) - (259.02 \times 273.04)}{\left[\sqrt{(7 \times 15378.12) - 259.02^2}\right]\left[\sqrt{(7 \times 13858.86) - 273.04^2}\right]} = 0.915$$

Alternatively, verification was carried out using $q_s = be^{-k_1 t}$. The result is presented in Table 4, and it can be seen that the coefficient of correlation after verification was 0.915, which indicates that the model $q_s = be^{-k_1 t}$ is adequate.

4.1.2 Case II

If time t is not large (i.e. at the initial stage of application of sludge into the drying bed).

Then $a \neq 0$. Therefore the value of a can be determined by trial and error in which .

Recall that from Equation (8); $q_s = a + be^{-k_1 t}$

$$\therefore q_s - a = be^{-k_1 t} \quad (18)$$

Linearizing Equation (18) we have;

$$\ln(q_s - a) = \ln b - k_1 t \quad (19)$$

Different values of a were substituted in the Equation (19) by trial and error to generate different sets of data which were regressed on time t, and the set which gave the highest value of coefficient of correlation 'r' was taken as the value of 'a'. Table 5 is a typical example of trial and error exercise when 'a'$= 2$, and the same practice was done using 'a' = 3, 4, 17.5, 18 and 18.4999. This exercise serves as calibration for seepage model case II.

Odd number data corresponding to days 1 to 15 were used for calibration and even number data were used for verification.

Figure 3 is a plot of variation of $\ln(q_s - a)$ with time when 'a'= 2, the same thing was done for 'a' = 3, 4, 17.5, 18 and 18.4999 respectively.

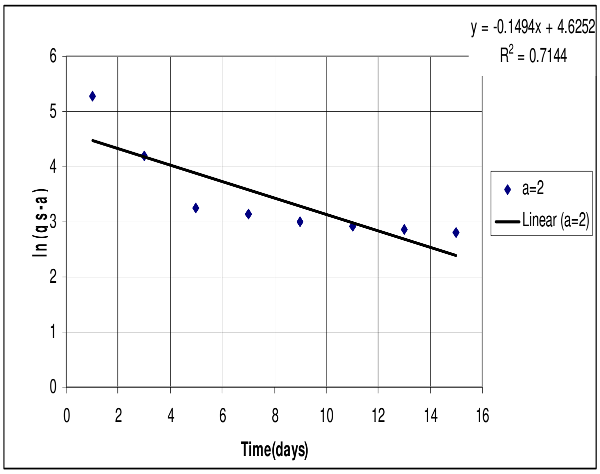

Figure 3: Variation of $\ln(q_s - a)$ *with time when a = 2*

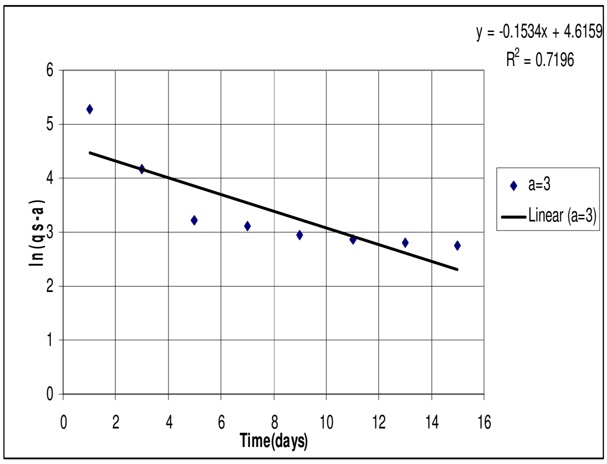

Figure 4: Variation of $\ln(q_s - a)$ *with time when a=3*

Table 5: Regression of time t on $\ln(q_s - a)$ when $'a' = 2$

$q_s \times 10^{-1}\ m^3$	$(q_s - 2)$	t	$\ln(q_s - a)$	t^2	$[\ln(q_s - a)]^2$	$t * [\ln(q_s - a)]^2$
196.41	194.41	1	5.2700	1	27.7729	5.2700
68.23	66.23	3	4.1931	9	17.5821	12.5793
27.79	25.79	5	3.250	25	10.5625	16.2500
25.39	23.39	7	3.1523	49	9.9370	22.0661
21.92	19.92	9	2.9917	81	8.9500	26.9253
20.67	18.67	11	2.9269	121	8.5667	32.1959
19.33	17.33	13	2.8524	169	8.1362	37.0812
18.50	16.50	15	2.8034	225	7.8591	42.0510

$$\sum t = 64 \quad \sum \ln(q_s - a) = 27.4328 \quad \sum t^2 = 680 \quad \sum [\ln(q_s - a)]^2 = 99.3665 \quad \sum t * [\ln(q_s - a)] = 194.4188$$

$$r = \frac{n\sum t * \ln(q_s - a) - \sum t * \sum \ln(q_s - a)}{\sqrt{n\sum t^2 - \left(\sum t\right)^2} * \sqrt{n\sum [\ln(q_s - a)]^2 - \left[\sum \ln(q_s - a)\right]^2}} = \frac{8(194.4188) - 64(27.4328)}{\sqrt{8(680) - 64^2} \times \sqrt{8(99.3665) - 27.4328^2}} = -0.83954$$

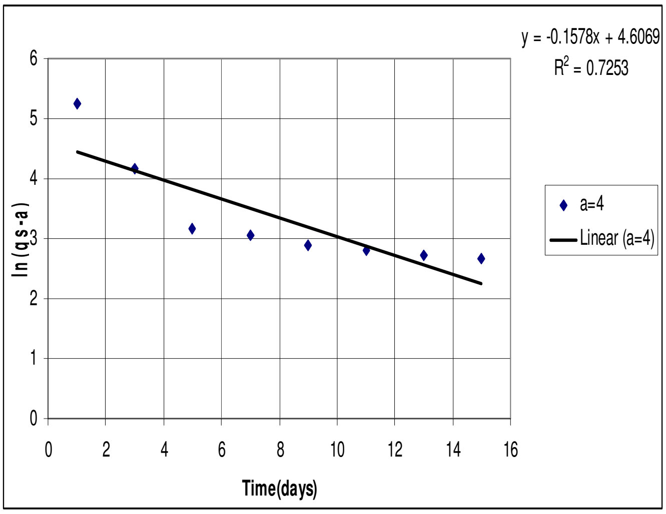

Figure 5: Variation of $\ln(q_s - a)$ with time when a=4

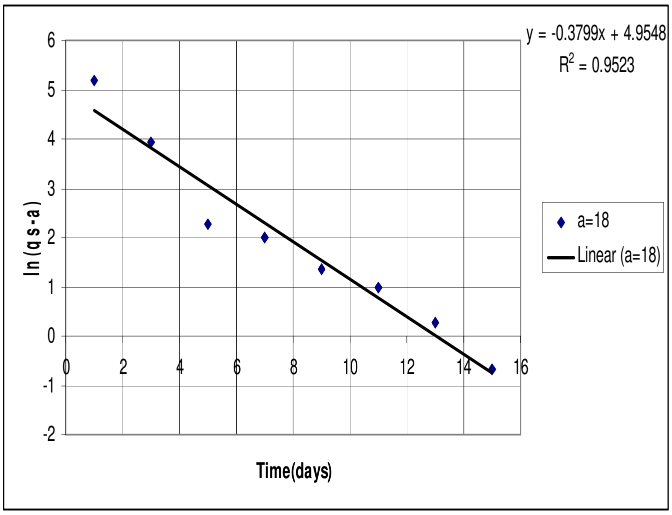

Figure 7: Variation of $\ln(q_s - a)$ with time when a=18.4999

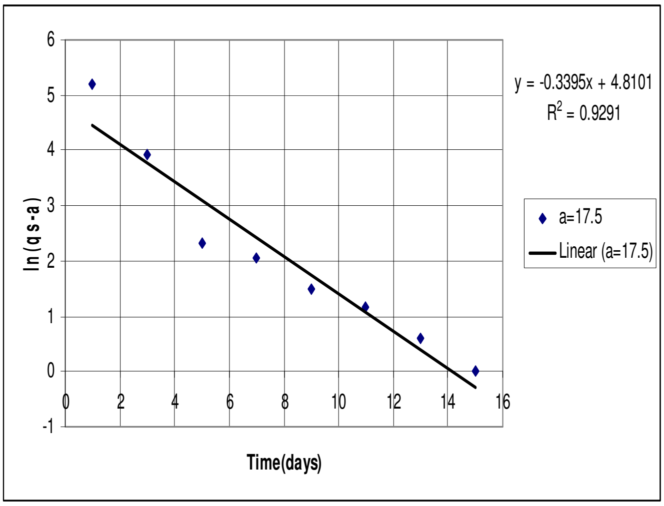

Figure 6: Variation of $\ln(q_s - a)$ with time when a=17.5

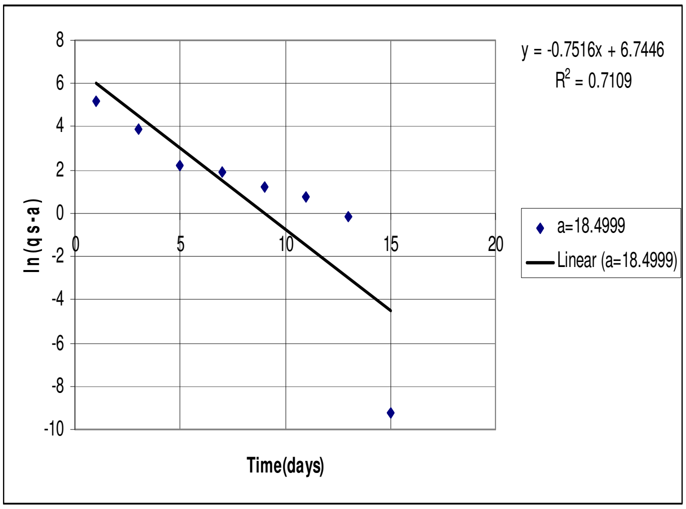

Figure 8: Variation of $\ln(q_s - a)$ with time When a=18

4.2 Determination of the Value 'a' by Trial and Error Method

When a = 18, highest coefficient of correlation exists between $\ln(q_s - a)$ and time as shown in Figure 7, therefore the value of a = 18.

Table 4: Verification of seepage model case II when a = 18

$t(days)$	$q_s \times 10^{-1}$ (m^3)	$q_s - a$	$\ln(q_s - a)$ Measured	$\ln(q_s - a)$ calculated
2	109.36	91.36	4.5148	4.1950
4	40.87	22.87	3.1298	3.4351
6	25.57	7.57	2.0242	2.6752
8	23.12	5.12	1.6332	1.91531
10	21.21	3.21	1.1663	1.1554
12	20.11	2.11	0.7467	0.3555
14	18.79	0.79	-0.2357	-0.3643

Let $x =$ measured $\ln(q_s - a)$ and $y =$ calculated $\ln(q_s - a)$

Table 5: Regression of measured and calculated quantities of $\ln(q_s - a)$

x	y	x^2	y^2	xy
4.5148	4.1950	20.3834	17.5980	18.9396
3.1298	3.4351	9.7956	11.7999	10.7512
2.0242	2.6752	4.0974	7.1567	5.4151
1.6332	1.91531	2.6673	3.6684	3.1281
1.1663	1.1554	1.3603	1.3350	1.3475
0.7467	0.3555	0.5576	0.1264	0.2655
-0.2357	-0.3643	0.0556	0.1327	0.0859

$\sum x = 12.9793$ $\sum y = 13.3672$ $\sum x^2 = 38.9172$ $\sum y^2 = 41.8171$ $\sum xy = 39.9329$

Table 6: Regression of measured and calculated q_s for seepage model case II

$t(days)$	x	y	x^2	y^2	xy
2	109.36	84.3504	11959.610	7114.610	9224.560
4	40.87	49.0336	1670.357	2404.294	2004.003
6	25.57	32.5151	653.825	1057.232	831.411
8	23.12	24.7412	534.534	612.127	572.017
10	21.21	21.1754	449.864	448.398	449.130
12	20.11	19.4852	404.412	379.673	391.847
14	18.79	18.6947	353.064	349.492	351.273

$\sum x = 259.03$ $\sum y = 249.996$ $\sum x^2 = 16025.666$

$\sum y^2 = 12366.206$ $\sum xy = 13824.241$

Regressing, $r = 0.9734$

This high $r - value$ shows that the model is satisfactory.

Since $a = 18$, $\ln b = 4.95483$ and $k_1 = 0.37994$

$b = e^{4.95483}$, Then $b = 141.8585$

$$\Rightarrow q_s = 18 + 141.8585 e^{-0.37994t}$$

This later model can be used for verification as shown below.

Also, Let $x =$ measured q_s and $y =$ calculated q_s.

Regressing, $r = 0.972$

This high $r - value$ shows that the model is satisfactory.

5. CONCLUSION

Sewage sludge drying beds are effective means of management and treatment of sewage sludge derived from households' septic systems. Rather than discharging the wastes into the environment untreated, thereby causing diseases spread, it is better to handle the waste using drying beds. This is evident from the seepage model developed in this study which would be a very good guide in the design of drying beds. The model will assist tremendously in achieving a design that would satisfy economic, aesthetic and durability requirements.

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