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A Study of Evaporation from Sewage Sludge Drying Beds and Investigation of Swanwick's Model

J. I. Obianyo[a*], J. C. Agunwamba[b] and B. Ajulibe[b]

[a]Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria
[b]Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria

***Corresponding Author:** obianyo.jude@mouau.edu.ng*

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ABSTRACT

This study was undertaken to investigate the evaporation of water from sewage sludge in drying beds in order to determine the Swanwick's evaporation factors and the possibility of their applicability in design of sand drying beds in other regions of the world. Sewage sludge of approximately equal initial moisture contents were introduced into four drying beds A, B, C, and D with different exposure conditions. Draining took place for 6 days, while evaporation was allowed for 54 days. Data obtained for the first 45 days of evaporation was used for computation of sludge evaporation and rainfall absorption factors. Statistical t-test was carried out at 1% level of significance to verify the difference between the rainfall parameters. Sewage sludge evaporation factors were 0.78, 0.73, 0.75, 0.98 for beds A, B, C, D, while it was 0.75 for Swanwick's model. Coefficient of variation for between these factors for beds A to D was 0.142198 while coefficient of variation for Swanwick model (0.75), beds A, B, C, and D taken together was 0.12944 which are insignificant. The sludge rainfall absorption factor for bed C was 0.26 and differs so much from Swanwick's value of 0.57, a decrease in value of 49.12% which could be attributed to climatic factors not considered in this study. Test of hypothesis at 1% significance level showed that calculated t-score -3.42, -3.34, -2.57 and -2.64 for beds A, B, C, and D were less than tabulated t-score of 3.36 which satisfy the null hypothesis that there is no difference in the measured and predicted sludge depth change. Goodness of fit between sludge evaporation factors derived from Excel plot and least square method was 0.987, while that between time and sludge depth change was 0.995. It was concluded that Swanwick's sludge evaporation factor is acceptable.

1. INTRODUCTION

Suspended solids are found in wastewater treatment plants and they originate from raw wastewater. These solids contain organic and inorganic pollutants, and pathogenic microorganisms from which diseases are transmitted in the environment (Elbaz *et al.*, 2020). Sludge production during wastewater treatment is a function of many factors which include, climate, culture consumption habits and treatment technologies among others (Al-Malack *et al.*, 2002). The sewage sludge which is the solid content of wastewater has to be treated by dewatering and removal of organic matter to make them amenable for reuse or disposal to the environment in harmless form (Gabrielli *et al.*, 2015; Tonetti *et al.*, 2018).

Every year, large amounts of wastewater sludge are generated worldwide. The European Commission reported an increase in sludge production of 3.5 million tonnes of dry matter, from 5.5 million tonnes in 1992 to 9 million tonnes of dry matter in 2005, which could increase to 13 million tonnes in 2020 (European Commission, 2012). In sewage sludge treatment, better performances are achieved with the use of drying beds because of higher quantities of solid content generation and volume reduction over a short period of time (Lamperia, 2017). It is simple since it does not require mechanical means to operate, the sludge is spread out and allowed to dry where greater parts of the water are discharged through under drains while the remaining evaporate until the required solids content is attained (Strande *et al*., 2014).

Sewage sludge produced from wastewater represents a real challenge to handling and management techniques. The huge amounts of sludge produced and the problems associated with its mode of disposal motivated many researchers to conduct their studies on sludge management. The management of sludge depends largely on their composition and properties that are related mostly to the source of their original wastewater, the type of treatment process they are subjected to, and the type and nature of chemicals used in the treatment processes (Al-Otoom *et al*., 2015). For thermal characteristics of sewage sludge, Jung *et al*. (2000) reported that increase in temperature resulted in corresponding increase in volatile matter and a decrease in char production. Rate of evolution of volatile matter had strong correlation with pyrolysis temperature with emissions of CO_2, H_2, CO, CH_4 and C_2H_4 gases at different pyrolysis temperatures. The primary aim of drying beds is to dewater the sludge so that it will be easier to manage. Various disciplines use different nomenclature for the types of water associated with sludges (Adrian, 1978). Four categories of municipal sludge moisture include the free moisture, immobilized water, bound moisture and chemically bound moisture (Smollen, 1988).

The presence of organic nutrients makes the use of sludge a supplement to fertilizer and an attractive option (Ahmed *et al*., 2010; Sohaili *et al*., 2012). Kyncl (2008) used dried sludge as a source energy for cement industry since it can be treated with high heating values between 12000 and 16000 kJ/kg. Fang *et al*. (2010) also used it in the carbonaceous adsorbent production for tertiary treatment of wastewater. Tsai (2012) conducted the feasibility studies of using sludge to produce biochar, and found out that it is a very good material for biochar production due to its high heating value and low production cost. Many other researchers conducted the feasibility studies of producing biodiesel from sludge and concluded that it could be one of the most promising feedstock for biodiesel production (Revellame *et al*., 2010; Mondala *et al*., 2009; Dufreche *et al*., 2007; Pastore *et al*., 2013).

Models for Estimation of Losses in Drying Beds

A number of models have been developed for estimation of drying of sludge in sand beds. Seginer and Bux (2005) developed a mathematical model for prediction of evaporation losses in a drying bed of sludge derived from septic tank, the model is expressed as in equation 1;

$$E = \rho(w_{out} - w_{in})Q_v \equiv \rho \Delta w Q_v \qquad (1)$$

where: E is the evaporation rate (kg/m^2.s), w is the humidity ratio, w_{out} and w_{in} are the humidity ratios of the ventilating air at outlet and inlet metal pipes, ρ is the density of air (g/cm^3) and Q_v is the discharge(mm^3/s) of the ventilating fans respectively.

Water evaporates slower from sludge than from clean water and rainfall tends to increase the moisture content of sludge in open air sand drying bed (Agunwamba, 2001). Swanwick (1963) showed that sludge evaporation was about 75% of that of clean water ($a = 0.75$), while rainfall added extra moisture to sludge reducing evaporation to about 57% ($b = 0.57$). Vesilind *et al.* (2009) corroborated this idea when they stated that the rate of moisture loss in sand beds was approximately 75% of the loss from clean water surface and about 57% of the rainfall absorbed by the sludge. However, Ceronio *et al.* (1999) while investigating Swanwick equation in South Africa and verifying 75% sludge evaporation factor observed that the rainfall absorption can vary between 20 to 40% for different rainfall levels and differently digested sludge.

Swanwick (1963) model for sand drying bed (SDB) is a rational equation and may be expressed as presented in equation 2:

$$A = \frac{QT}{H} \quad (2)$$

where: A is the surface area of drying bed (m^2); Q is the volume flow rate of sludge (m^3/day); H is the sludge application depth on the bed (m); T is the sludge drying time (days) and it is defined as presented in equation 3.

$$T = t_1 + t_2 \quad (3)$$

where; t_1 is the sludge draining time (time during which draining dominates water loss from sludge) (days); t_2 is the sludge evaporation time (time during which evaporation dominates water loss from sludge) (days). Thus, Swanwick (1963) is given by the equation 4. Substituting t_2 in equation 3 gives equation 5.

$$t_2 = \frac{30HS_0}{aE-bR}\left[\frac{1}{S_1} - \frac{1}{S_2}\right] \quad (4)$$

$$T = t_1 + \frac{30HS_0}{aE-bR}\left[\frac{1}{S_1} - \frac{1}{S_2}\right] \quad (5)$$

in which S_0 is the initial percent solid content of sludge (%); S_1 is the percent solid content of sludge after draining (%); S_2 is the target or desired percent solid content after evaporation (%); R is the average rainfall (mm/month); E is the clean water evaporation (mm/month); $a =$ sludge evaporation factor (SEF); aE is the sludge water evaporation in relation to clean water evaporation based on sludge evaporation factor (mm); bR is the amount of rainfall absorbed by sludge based on sludge rainfall absorption factor (mm); b is the rainfall absorption factor (RAF); $aE - bR$ is the effective evaporation from sludge.

If a sludge is applied to a bed at time 't_0', (days) to a depth 'H_0' (m) and percent solid content 'S_0' (%) and the sludge becomes drained to percent solid content 'S_1' (%) after which it becomes evaporated until solid content 'S_2', then level or depth of water evaporated will be given by the expression in equation 6 (Swanwick 1963);

$$\Delta H = H_0 S_0\left[\frac{1}{S_1} - \frac{1}{S_2}\right] \quad (6)$$

Where: ΔH is the sludge depth change (mm); H_0 is the depth at time $t = 0$; S_0 is the percent moisture content at time $t = 0$; S_1 is the percent moisture content after draining; and S_2 is the percent moisture content after evaporation.

Adrian (1978) proposed a model for the determination of drainage times in drying beds given by the expression shown in equations 7 and 8.

$$t = \frac{\mu R_c f}{\rho g (H_c)^{\sigma}(\sigma+1)}\left[\frac{H_0^{\sigma+1}}{\sigma} + H^{\sigma+1} - \frac{\sigma+1}{\sigma} H_0 H^{\sigma}\right] \quad (7)$$

Where t is the drainage time (s); μ is the viscosity (g/s.cm); R_c is the specific resistance (s^2/g) at reference pressure H_c (cm); ρ is the density (g/cm^3); g is the acceleration due to gravity (cm/s^2); H_0 is the depth of sludge (cm) at t_0 and H is the depth of cake (cm) at t; σ is the compressibility factor.

$$f = \frac{\rho g}{\left(\frac{100}{S_0} - \frac{100}{S_1}\right)} \quad (8)$$

where S_0 is the per cent sludge solids before drainage and S_1 is the per cent sludge solids at completion of drainage. If $100/S_1$ is negligible, and substituting $\frac{\rho g}{100/S_0}$ for f in (7) result in equation 9;

$$t = \frac{\mu R_c S_0}{100(H_c)^{\sigma}(\sigma+1)}\left[\frac{H_0^{\sigma+1}}{\sigma} + H^{\sigma+1} - \frac{\sigma+1}{\sigma} H_0 H^{\sigma}\right] \quad (9)$$

The denominator $1/(\sigma+1)$ can be included into the second half of equation (7) to give equation 10;

$$t = \frac{\mu R_c S_0 S_1}{100(S_0 - S_1)H_c^{\sigma}}\left[\frac{H^{\sigma+1} - H_0^{\sigma+1}}{\sigma+1} + \frac{H_0^{\sigma+1} - H_0 H^{\sigma}}{\sigma}\right] \quad (10)$$

Adrian (1978) suggested the use of equation (9) for wastewater sludges, where: $S_1 \gg S_0$, but for water treatment sludges, a modified equation (10) is suggested which includes amongst others a media factor. The Walski (1976) model was formulated to estimate the total bed area as in equation 11a;

$$A_T = \frac{q_s}{H_0} T \quad (11a)$$

The main feature of this model is the estimation of time T, which is the time for both gravity drainage t_1, and evaporation t_2, given by the expression in equation 11b;

$$A_T = \frac{100.q_s}{H_0}\left[t_1 + \frac{30 H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right)\right] \quad (11b)$$

Where:
A_T is the total bed area (m^2), q_s is the sludge production (m^3/s), H_0 is the bed loading depth (cm) at t_0
t_1 is the gravity drainage time (d), (to be determined experimentally by laboratory analysis)
t_2 is the evaporation time (d), S_0 is the % solids concentration at t_0, S_1 is the % solids concentration at t_1
S_2 is the % solids concentration at t_2, R is the monthly rainfall (cm), E is the monthly evaporation (cm)
a is the factor for evaporation from sludge relative to clean water, b is the rainfall absorption factor by sludge, $aE - bR$ is the effective evaporation $(cm/month)$, T is the total dewatering time $(t_1 + t_2)$ (days)
The variable $t_2 =$ is expressed as in equation 12;

$$t_2 = \frac{30 H_0 S_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \quad (12)$$

Therefore, this study was undertaken to study evaporation of water from sewage sludge in sand drying beds in order to investigate the Swanwick's evaporation factors and possibility of their applications in design of sludge drying beds in other regions of the world like Africa. Many models have been proposed for prediction of losses in sludge drying beds, some empirical and others rational and notable among these models is that proposed by Swanwick (1963). This model uses empirically determined evaporation factors namely sludge evaporation factor, $a = 0.75$ and sludge rainfall absorption factor, $b = 0.57$, determined in England in 1963. Design of sewage sludge drying beds using the Swanwck's evaporation and absorption factors may lead to erroneous designs if these factors cannot be universally applied, and this concept led to this research for validation of these constants for applicability in other parts of the world.

2. METHODOLOGY

2.1 Sample Collection

The sewage sludge used in this study was obtained from septic tank serving the Males Hostel of Michael Okpara University of Agriculture, Umudike, Nigeria.

2.2 Experimental Procedures

The sludge characteristics such as pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total carbon (TC), moisture content, TBH, total nitrogen, phosphorus and potassium were determined using standard methods contained in the Manual of Methods of Analysis of Foods (2016). Four drying beds were used to conduct experiments in this research to determine sludge evaporation factor '*a*' and the sludge rainfall absorption factor '*b*'. The drying beds used was 1.0 m long, 0.3 m wide and 0.7 m deep and a perforated drain pipe of 50 mm diameter fixed at the bottom which extended outside the bed for collection of effluent. It is a simple sand and gravel filters on which batch loads of sludge are dewatered. A gravel layer, 200 mm thick, with grain diameter size ranges of 7 - 15 mm was introduced inside the bed, on the bottom and directly on top of the drainpipe. On top of the gravel layer was a final sand layer 200 mm thick with grain size diameter ranges of 0.2 - 0.6 mm. Four drying beds were used in this study A, B, C, and D respectively. Beds A and B were kept under tarpaulin canopy cover to avoid ingress of rain water, bed C was kept in the open space and exposed to rainfall and sunshine while bed D was kept in the open space and covered with clear plain glass during rainfall and exposed when there was no rain.

The depths of the sludge were the same and some samples of the sludge were taken to the laboratory and the moisture content determined with the aid of an electric oven, which were approximately equal at the beginning of the experiment. Draining took place for 6 days and evaporation was measured for 54 days with the aid of the electronic atmometer Type 7061.0000BG which permits the measuring of evaporation rate at free surfaces of water. The experiments were conducted in the months of September and October, 2015. Data obtained was used for modeling evaporation from the sludge and the Swanwick (1963) model was also investigated. This was carried out by test of hypothesis at 1% level of significance using the student t-test to ascertain if there is significant difference in the measured and predicted sludge depth change. The sludge evaporation and rainfall absorption factors obtained from this study were compared with Swanwick’s evaporation and rainfall absorption factors by computing coefficient of variation between them. Also, sludge evaporation factors (SEF) derived from Excel plots were compared with SEF computed from the least square method using coefficient of correlation, and this assisted in validation of Swanwick’s model.

Coefficient of variation was computed to know the degree of variability of sludge evaporation and rainfall absorption factors obtained in this study and that derived by Swanwick (1963). Also, coefficient of correlation between sludge evaporation factors derived from Excel plots and those computed from least square method was determine for verification purpose.

2.3 Modifying the Swanwick's model for water evaporation from sludge

Modification of Swanwick's model is essential in order to convert the model to a linear function of the form $y = mx + c$, for computation of the sludge evaporation factor 'a' and rainfall adsorption factor 'b' by linear regression. The basis for Swanwick's sludge evaporation model is that the volume of water loss in the sludge, ΔH , during evaporation which is equal to the sludge effective evaporation (aE - bR) multiplied by the number of days (t) during which the loss occurs. Equation 13 represents this reasoning. If evaporation and rainfall data are given in (mm/month), the effective evaporation can be divided by 30 to convert it to days. Rearranging Equation 14 we obtain equation 15.

$$H_0S_0\left[\frac{1}{S_1}-\frac{1}{S_2}\right] = [aE - bR]t \quad (13)$$

$$H_0S_0\left[\frac{1}{S_1}-\frac{1}{S_2}\right] = \frac{aE-bR}{30}.t \quad (14)$$

$$t = \frac{30H_0S_0}{aE-bR}\left[\frac{1}{S_1}-\frac{1}{S_2}\right] \quad (15)$$

Basis for sludge evaporation factor experimental design

If sludge drying bed is under cover, there will be no rainfall ingress. Also, if sludge is evaporated in such a way as to avoid rainfall ingress ($bR = 0$), then sludge effective evaporation ($aE - bR$) will reduce to 'aE' and the Swanwick model can be adjusted as equation 16. Rearranging equation 16 and recognizing that gives the expressions in equations 17 and 18.

$$t = \frac{30H_0S_0}{aE}\left[\frac{1}{S_1} - \frac{1}{S_2}\right] \quad (16)$$

$$\Delta H = H_0S_0\left[\frac{1}{S_1} - \frac{1}{S_2}\right]$$

$$t = \frac{30\Delta H}{aE} \quad (17)$$

$$\therefore\ \Delta H = \frac{aEt}{30} \quad (18)$$

At time $t = 0$, $\Delta H = 0$; at time $t = 0$, $\Delta H = 0$,

Equation 18 is similar to a linear function of the form $y = mx + c$ in which $y = \Delta H$, $c = 0$, (intercept), the slope, $m = \left(\frac{aE}{30}\right)$ and $t = x$. The slope of this plot can be obtained by linear regression or Excel plot. The evaporation factor '*a*' can then be evaluated since the clean water evaporation '*E*' is known ('*E*' obtained from weather station).

2.3.2 Basis for sludge rainfall absorption factor 'b' determination

Rearranging equation 16 and recognizing that;

$$\Delta H = H_0S_0\left(\frac{1}{S_1} - \frac{1}{S_2}\right)$$

We obtain the expression in equation 19;

$$t\left(\frac{aE-bR}{30}\right) = \Delta H \quad (19)$$

Applying boundary conditions on equation 19 we obtain, at time $t = 0$, $\Delta H = 0$. There is no sludge level change at the beginning of evaporation process. Therefore, equation 19 is a linear function

$$y = mx + c \quad (20)$$

In which $y = \Delta H$, $c = 0$ (i.e. intercept), $m =$ slope $\left(\frac{aE-bR}{30}\right)$ and $t = x$

Therefore obtaining sludge level changes ΔH against time (*t*) during evaporation in the presence of rainfall and a plot of the level changes against time '*t*' will give the expression in equation 21.

$$m = \left(\frac{aE-bR}{30}\right) \quad (21)$$

Data analysis was carried out for sludge beds A, B, C and D respectively using linear regression and Excel plot to determine lines of best fit (i.e. linear models). The linear models were used to determine sludge evaporation factors and sludge rainfall absorption factors. Monthly evaporation data (E) from the Nigerian Meteorological Agency (NIMET) = 73.1mm

Computing the sludge evaporation factor (SEF) using equations 22 and 23.

$$m = \frac{n\sum x_i \sum y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2} \quad (22)$$

$$c = \bar{y} - m\bar{x} \quad (23)$$

Where x_i = any given day, y = sludge depth change and n = 45 days of evaporation

The slope of this plot can be obtained by linear regression or plot. Having obtained sludge evaporation factor '*a*' previously from the sludge evaporation factor experiment, and knowing the average rainfall '*R*' and average clean water evaporation '*E*', the sludge rainfall absorption factor '*b*' was evaluated from the slope of the plot.

Calculation of *t*-score for drying beds

Consider equations 24 to 26.

Variance, $s_d^2 = \frac{\sum_{i=1}^{N}(y-\bar{y})^2}{N-1}$ (24)

Standard deviation, $s_d = \sqrt{\frac{\sum_{i=1}^{N}(y-\bar{y})^2}{N-1}}$ (25)

t-score$= \frac{\bar{y}-\mu}{s_d/\sqrt{N}}$ (26)

s_d is the standard deviation, y is the mean of sludge depth change (mm), $\bar{y}$ is the mean of predicted sludge depth for days 46 to 54, μ is the mean of measured sludge depth change for days 46 to 54, N is the number of data points (i.e. 9 days), $N-1$ is the degree of freedom ($df = 8$).

To accomplish this comparison, the models were subjected to test of hypothesis at 1% significance level and 8 degrees of freedom. These were the null hypothesis H_0 and alternative hypothesis H_1 respectively thus; H_0: $\bar{y} = \mu$ and there is no significant difference in the measured and predicted sludge depth change, if any, it is merely due to chance. H_0: $\bar{y} \neq \mu$ and there is significant difference in the measured means and the predicted sludge depth change. We further determined the coefficient of variation (CV) for sludge evaporation factor "a" given by the expression shown in equations 27 to 29.

$CV = s/\bar{a}$ (27)

Where $\bar{a}$ is the mean value of sludge evaporation factors and "s" is the standard deviation given by the expression;

$s = \sqrt{\frac{\sum(a-\bar{a})^2}{N-1}}$ (28)

where a = evaporation factor

Goodness of fit between variables wherever applicable was computed using the product moment method as shown;

$r_{x_i y_i} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{[n\sum x_i^2 - (\sum x_i)^2][n\sum y_i^2 - (\sum y_i)^2]}}$ (29)

Where x_i = any given day, *yi* = sludge depth change (mm) and n = 45 days of evaporation

2.4 Sludge Evaporation Factor

Referring to Figure 2, the equation of the curve is $y = 1.913x + 3.643$

Recall from equation 18;

$\Delta H = \frac{aEt}{30}$ Here $\Delta H = y$, $t = x$ and $\frac{aE}{30} = 1.913$ (i.e. slope of the linear function $y = 1.913x + 3.643$)

$1.913 = \frac{73.1a}{30}$, here the parameter $E = 73.1\ mm$

$a = 0.785089$ (Sludge evaporation factor for Bed A).

The parameter $E,$ is a secondary data known as the Monthly average evaporation over a period from 1st January, 2013 to 1st September, 2014 got from the Nigerian Meteorological Agency (NIMET). This long duration was considered in order to have monthly average temperature that would be true representative of rainfall pattern in this locality. In a similar way, Figures 4, 6 and 8 were used to compute sludge evaporation factors for Beds B, C and D respectively.

2.5 Development of Models

Using the least square method to determine the slope *m* and the intercept *c* from the equation

$y = mx + c$

$s_d^2 = \frac{\sum_{i=1}^{N}(y-\bar{y})^2}{N-1}$

Recalling equations 22 and 23;

$m = \frac{n\sum x_i \sum y_i - \sum x_i \sum y_i}{n\sum x_i^2 - (\sum x_i)^2}$

$\bar{y} = m\bar{x} + c$

Where x_i = Number of days and y_i = sludge depth change as in Figure 2 above for days 1 to 45. Substituting the values and solving;

$m = 1.9022398$ and $c = 4.004040156$

From the values of *m* and *c* calculated above, the linear model for sludge drying Bed A may be proposed as in equation 30.

$$y = 1.9022398x + 4.004040156 \qquad (30)$$

Table 6, also calculated sludge depth change was computed for 16/04/2015 in which $'x'$ was 46 and $y = 1.902(46) + 4.004 = 91.496$, (Table 4). In the same manner sludge depth change was calculated for 17/04/2015 to 24/04/2015 and such computations were done for Beds B, C and D respectively using Figures 4, 6 and 8.

2.6 Computation of Sludge Rainfall Absorption Factor

Bed C was the only one kept in the open space and exposed to rainfall and sunshine and as result has the tendency to absorb moisture from the atmosphere, hence the computation of rainfall absorption factor 'b'. Referring to Figure 6;

$y = 1.825x - 1.139$

Effective evaporation $= aE - bR$

$bR = 1.139 \times 45 =$ rainfall absorption.

Given $R = 194.1\ mm$ which is the average monthly rainfall from 1st January, 2013 to 1st September, 2014 a secondary data got from NIMET.

Rainfall absorption factor $b = \frac{1.139 \times 45}{194.1} = 0.26$ (Table 8)

3. RESULTS AND DISCUSSION

The results of the sludge characteristics at the beginning of experiments are presented in Table 1. Table 2 shows the depth of sludge at the beginning of experiment, depth after 6 days of draining prior to commencement of evaporation and depth after 45 days of evaporation for beds A, B, C and D. It also depicted the moisture content conditions at application of sludge, after 6 days of draining before start of evaporation. Moisture content after 45 days of evaporation and the daily average evaporation from the sludge for beds A, B, C and D respectively. Figures 1 to 8 presented the plots of variation of sludge depth change with time for over a period of 45 days for model with zero intercept and model with intercept for beds A, B, C and D.

Table 1: Sludge characteristics at beginning of experiment (1st September, 2015)

Parameter	Category	Results
Ph	Chemical	8.01
BOD	Chemical	357 mg/l
COD	Chemical	8000 mg/l
TC	Chemical	9600 mg/l
Moisture content	Physical	94.5%
TBH (cfu/ml)	Biological	1.19×10^3
Total Nitrogen	Chemical	12 %/g
Phosphorous	Chemical	5 %/g
Potassium	Chemical	3 %/g

Table 2: Variation of sludge depth, moisture content and daily average evaporation with time

	Depth of Sludge (mm)			Moisture Content (%)			
Bed Tag No.	**At Application (i.e. Day 1)**	**At End of Draining/Commencement of Evaporation. (i.e. After 6 Days of draining)**	**After 45 Days of Evaporation**	**At Application (i.e. Day 1)**	**At End of Draining/Commencement of Evaporation. (i.e. After 6 Days of draining)**	**After 45 days of Evaporation**	**Daily Ave. Sludge Evap. (mm)**
A	270	246	151	92.4	93	88.5	2.11
B	270	241	157	93.7	94	89.0	1.87
C	270	241	157	94.5	94.5	91.9	1.87
D	270	241	130	94.0	92.5	88.1	2.47

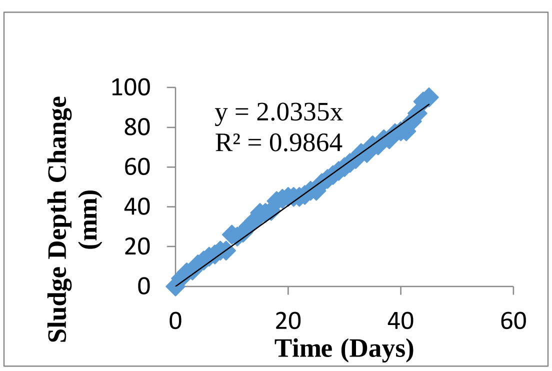

Figure 1: Variation of sludge depth change with time for Bed A for 0 to 45 days (model with zero intercept)

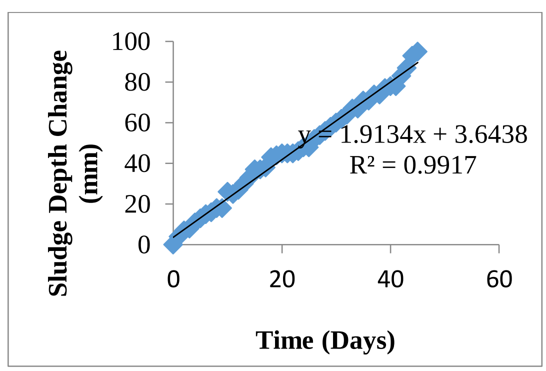

Figure 2: Variation of sludge depth change with time for Bed A for 0 to 45 days (model with intercept)

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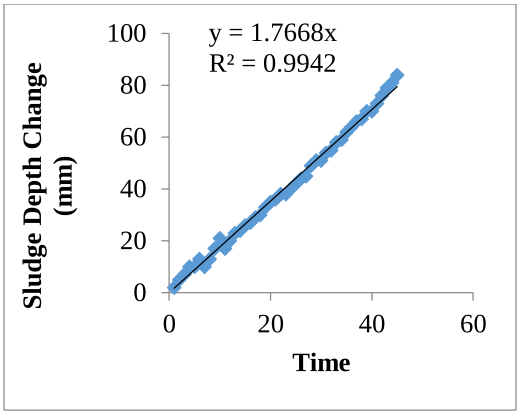

Figure 3: Variation of sludge depth change with time for Bed B for 0 to 45 days (model with zero intercept)

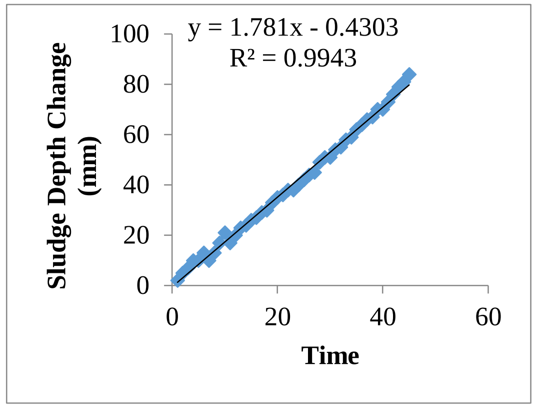

Figure 4: Variation of sludge depth change with time for Bed B for 0 to 45 days (model with intercept)

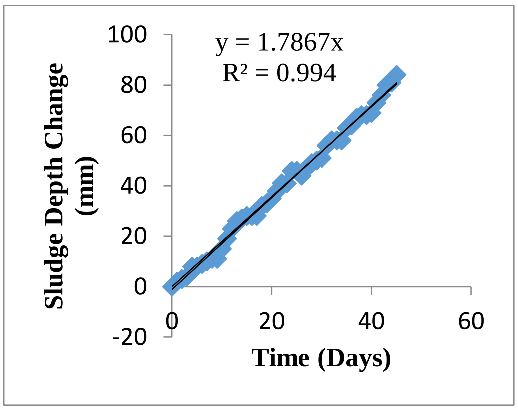

Figure 5: Variation of sludge depth change with time or Bed C for 0 to 45 days (model with zero intercept)

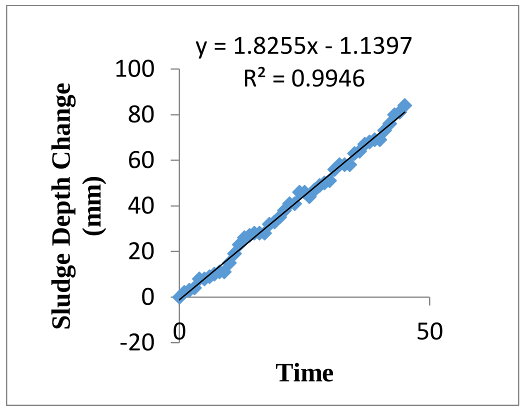

Figure 6: Variation of sludge depth change with time for Bed C for 0 to 45 days (model with intercept)

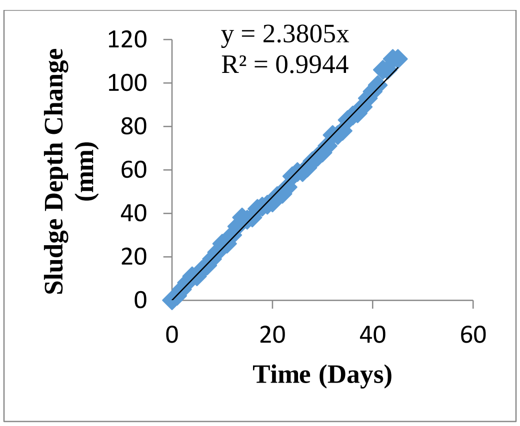

Figure 7: Variation of sludge depth change with time for Bed D for 0 to 45 days (model with zero intercept)

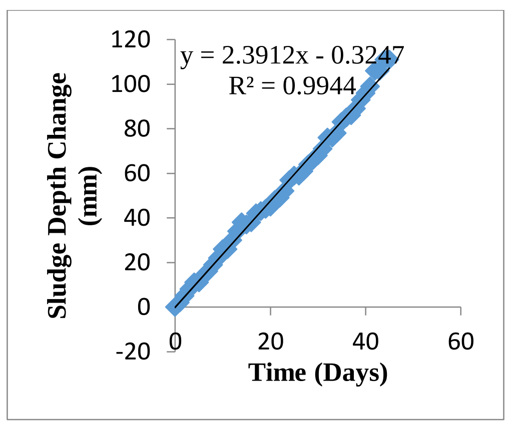

Figure 8: Variation of sludge depth change with time for Bed D for 0 to 45 days (model with intercept)

Computation of t-scores, Sludge Evaporation and Sludge Rainfall Absorption Factors

Computation of t-score for Bed A

Bed A; Excel Method - Model without intercept (Table 3)

$s_d = \sqrt{\frac{247.98}{9-1}} = 5.5675$, t-score $= \frac{101.65-104.89}{5.5675/\sqrt{9}} = -1.75$

In a similar manner, t-scores for all the models were computed using data for days 46 to 54 and the results are presented in Table 7.

Calculated sludge depth change on 16/10/2015 was $y = 2.033(46) = 93.52$,

Table 3 presents the computation of t-score for bed A at 1% level of significance for model with zero intercept. In a similar manner t-scores for beds B, C and D were computed. Table 4 presents the computation of t-score for bed A at 1% level of significance for model with intercept. In a similar manner t-scores for beds B, C and D were computed.

Table 3: Computation of variance, standard deviation and t-score for Bed A based on the equation y = 2.033x

Date	Day No. (x)	Measured Sludge Depth Change (y) (mm)	Calculated Sludge Depth Change (mm) y = 2.033x	y-ȳ	$(y-\bar{y})^2$	t- score
16/10/2015	46	96	93.52	-8.13	66.10	
17/10/2015	47	96	95.55	-6.10	37.21	
18/10/2015	48	101	97.58	-4.07	16.56	
19/10/2015	49	101	99.62	-2.03	4.12	
20/10/2015	50	103	101.65	0	0	-1.75
21/10/2015	51	109	103.68	2.03	4.12	
22/10/2015	52	109	105.72	4.07	16.56	
23/10/2015	53	114	107.75	6.10	37.21	
24/10/2015	54	115	109.78	8.13	66.10	
	Mean	μ = 104.89	ȳ = 101.65		∑ = 247.98	

Table 4: Computation of variance, standard deviation and t-score for Bed A based on predicted regression model *y* = 1.902*x* + 4.004

Date	Day No. (x)	Measured Sludge Depth Change (y_m) (mm)	Calculated Sludge Depth Change (mm) *y* = 1.902*x* + 4.004	y-ȳ	$(y-\bar{y})^2$	t- score
16/10/2015	46	96	91.496	-7.497	56.205	
17/10/2015	47	96	93.398	-5.595	31.304	
18/10/2015	48	101	95.300	-3.693	13.638	
19/10/2015	49	101	97.202	-1.791	3.208	
20/10/2015	50	103	99.104	0.111	0.012	- 3.42
21/10/2015	51	109	100.006	1.013	1.026	
22/10/2015	52	109	102.908	3.915	15.327	
23/10/2015	53	114	104.810	5.817	33.837	
24/10/2015	54	115	106.712	7.719	59.583	

The goodness of fit of equation 23 was evaluated by finding the correlation coefficient between time (x_i) and sludge depth change (y_i) using (Eqn. 29); $r_{xy} = 0.995$, While that between sludge evaporation factors derived from Excel plots and least square methods was found to be $r_{xy} = 0.987$ Where *x* stands for sludge evaporation factor computed from Excel graphical plot and *y* for sludge evaporation factor calculated using the least square method. In a similar manner, evaporation factors were computed and models developed for Beds B, C, and D, the models are shown in Table 6 and evaporation factors shown in Table 8.

In Table 5, the sludge evaporation factors (SEF) and R^2 values for beds A, B, C and D are presented. It shows the sludge evaporation factors for models without intercept plotted in Figures 1, 3, 5 and 7, and sludge evaporation factors for models with intercepts plotted in Figures 2, 4, 6 and 8.

Table 5: Comparison of Excel plots for models without intercept and models with intercept from Figures 1-8

Bed Tag	Without Intercept (Figs. 1, 3, 5 and 7)			With Intercept (Figs. 2, 4, 6 and 8)		
	Model	R^2	SEF	Model	R^2	SEF
A	$y = 2.033x$	0.986	0.834337	$y = 1.913x + 3.643$	0.991	0.785089
B	$y = 1.766x$	0.994	0.724761	$y = 1.781x - 0.430$	0.994	0.730917
C	$y = 1.788x$	0.994	0.733789	$y = 1.825x - 1.139$	0.994	0.748974
D	$y = 2.380x$	0.994	0.976744	$y = 2.391x - 0.324$	0.994	0.981259

Table 6 shows the comparison of results of sludge evaporation factors obtained from Excel plots models and the models derived from the least square method (predicted). This was achieved by computing the coefficient of correlation between them. From the result, coefficient of variation for sludge evaporation factors in Beds A to D gave 0.142198. Also computing the coefficient of variation considering sludge evaporation factor obtained by Swanwick (0.75), and Beds A to D, it was found to be 0.12944. Coefficient of correlation '*r*' between sludge evaporation factors derived from Excel plots and least square methods was found to be $r_{xy} = 0.987$ which indicates a very strong fit.

Table 6: Comparison of models from Excel plots and models from least square method

Bed Tag	Models from Excel Plots (Figs. 2,4,6,8)			Models from Least Square Method (Predicted)		
	Model	R^2	SEF	Model	r_{xy}	SEF
A	$y = 1.913x + 3.643$	0.991	0.785089	$y = 1.902239x + 4.004040156$	0.995	0.780673
B	$y = 1.781x - 0.430$	0.994	0.730917	$y = 1.781028x - 0.430310667$	0.997	0.730928
C	$y = 1.825x - 1.139$	0.994	0.748974	$y = 1.8289855x - 1.244444278$	0.997	0.750609
D	$y = 2.391x - 0.324$	0.994	0.981259	$y = 2.392227x - 0.354554333$	0.997	0.981259

In Table 7, results of t-scores for beds A to D were presented. Test of hypothesis was conducted at 1% significance level to ascertain if there exists significant difference between models from Excel plots and models computed from least square method. Test of hypothesis at 1% level of significance by the student t-score using data for days 46 to 54, showed that calculated t-scores for beds A, B, C and D were -1.75, -3.35, -3.09 and -2.76 from Excel plots, while -3.42, 3.34, -2.57, and - 2.64 were obtained for beds A, B, C, and D from calculated regression model using the least square method. Comparing these with the tabulated t-score of 3.36, it was found that all the beds satisfied the null hypothesis that Swanwick model is accepted since no significant difference exist between the sludge evaporation factors. Only bed A with a t-score of 3.42 did not fall into this and does not satisfy this concept.

Table 7: Presentation of t-scores for Beds A to D using data for days 46 - 54

Bed Tag	**Excel Plot Without Intercept**		**Calculated Regression Model from Least Square Method**	
	Model	t-score	Model	t-score
A	$y = 2.033x$	-1.75	$y = 1.902x - 4.004$	- 3.42
B	$y = 1.766x$	-3.35	$y = 1.78103x - 0.4303$	- 3.34
C	$y = 1.788x$	- 3.09	$y = 1.828x - 1.244$	- 2.57
D	$y = 2.380x$	- 2.76	$y = 2.392x - 0.354$	- 2.64

Table 8 presented the results of sludge evaporation factors and sludge rainfall absorption factors for Swanwick's model for beds A, B, C and D. Plots of sludge depth change with time for a period of 45 days shown in Figures 1 to 8 were used to compute the sludge the sludge evaporation factors 'a' and rainfall absorption factor 'b' presented in Table 8. Sludge evaporation factors for beds A, B, C, and D from Excel plots were 0.785089, 0.730917, 0.748974 and 0.981259, while from the least square method the results were 0.780673, 0.730928, 0.750609 and 0.981259, it could be seen that there is no significant difference between sludge evaporation factors obtained from the two methods.

Table 8: Sludge evaporation factors from Swanwick model and developed models

Model/Bed	Sludge Evaporation Factor "a"	Sludge Rainfall Absorption Factor "b"
Swanwick Model	0.75	0.57
Bed A	0.78	Nil
Bed B	0.73	Nil
Bed C	0.75	0.26
Bed D	0.98	Nil

The coefficient of correlation between sludge evaporation factors obtained from Excel plots and least square method computed was found to be r = 0.987, this is a very strong fit and inferred that Swanwick model is acceptable. Coefficient of variation between sludge evaporation factors for beds A, B, C and D (0.78, 0.73, 0.75 and 0.98) was found to be 0.142198. Also computing the coefficient of variation between sludge evaporation factors for Swanwick (1963) model, beds A, B, C, and D (0.75, 0.78, 0.73, 0.75 and 0.98), it was found to be 0.12944. This is an indication that variation is not significant and Swanwick (1963) model is acceptable. Rainfall absorption factors was found to be 0.29 for bed C against 0.57 for Swanwick model which is 49.12% decrease and is highly significant. Vesilind *et al*. (2009), found evaporation factor to be 0.75 and absorption factor to be 0.57 in agreement with Swanwick's evaporation factors. However, Ceronio *et al*. (1999), investigating the work of Swanwick in South Africa, found evaporation factor to be 0.75 and absorption factor to lie between 0.20 and 0.40 respectively. The different absorption factors in different regions presents the limitations of applicability of Swanwick's 1963 model in design of sand drying beds. This scenario could be as a result of different climatic factors in different regions where these studies were carried out. It could also be as a result of climatic factors not considered in this study.

4. CONCLUSION

Sludge evaporation factors computed from the least square method were 0.78, 0.73, 0.75, and 0.98 for beds A, B, C, and D against 0.75 for Swanwick (1963) model, a coefficient of variation of 0.12944 which is so insignificant. Also coefficient correlation between sludge evaporation factors derived from Excel graphical plots and those calculated from least square method was found to be *r* = 0.987. This indicated that Swanwick model is authentic and can be used in the design of drying beds. The test of hypothesis using the student t-test showed that beds B, C, and D satisfied the null hypothesis that there is no difference in the measured and predicted means, if any, it is merely due to chance. It was only bed A that showed a difference between measured and predicted means. With three out of four beds agreeing with the null hypothesis, it is concluded that Swanwick (1963) model is acceptable for sludge evaporation factor. However, different rainfall absorption factors were obtained in different regions which is a major limitation of universal applicability of this model. These changes are indications of influence of climatic factors and it is recommended that each region should conduct research to ascertain the rainfall absorption factor in their locality for applications in design of sand beds in their region.

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