STRATIFICATION IN WASTE STABILIZATION PONDS II: MODELLING

UKPONG, E.C.[1], AGUNWAMBA, J.C.[2] and EGBUNIWE, N.[2]
[1]*Department of Civil Engineering, University of Uyo, Uyo, Akwa Ibom State, Nigeria.*
[2]*Department of Civil Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria.*

ABSTRACT

The occurrence of thermal stratification in waste stabilization ponds (WSPs) alters the flow pattern of the pond. Hence, its study is important for complete and accurate modelling of the waste stabilization pond. In this study, a mathematical model for prediction of thermal stratification and mixing in waste stabilization ponds was developed under completely mixed condition for each sub-layer. The solution was obtained by simple algebraic substitution and the results verified with data from the field waste stabilization pond at the University of Nigeria, Nsukka and Laboratory scale waste stabilization pond. The theoretical results compared favourably with the experimental observation with coefficients of correlation ranging from 0.7000 to 0.9999. The application of the model in pond designand evaluation were also presented.

Keywords: Waste stabilization pond; model, algebraic; completely mixed; stratification

INTRODUCTION

A wastewater stabilization pond (WSP) is an earthen basin which is designed to treat a variety of wastewater from domestic to complex industrial wastewaters. It functions under a wide range of weather conditions, from tropical to arctic, and can be used alone or in combination with other processes. If sufficient land is available, a WSP is a cost-effective. In addition, its operation is easy and its maintenance requirements are minimal.

Waste Stabilization Ponds (WSP) is designed to provide a controlled environment for wastewater treatment. Its size is established from theoretical and empirical relationships that give directly or indirectly an estimate of the hydraulic retention time needed to achieve a given effluent quality. However, many factors may cause disturbances in the flow pattern of a pond; one of the factors is thermal stratification, a natural phenomenon that is usually neglected in pond design.

When a WSP is thermally stratified, a density gradient exists and its internal vertical mixing is compromised [1]. In this situation the pond behaves as a series of superimposed liquid layers with different densities, each layer being stable at a certain depth, with the densest layer close to the bottom. Thermal stratification can be stable-persisting for months, or intermittent appearing for a few hours in the day [2-4].

Thermal stratification, which is characterized by a high vertical thermal gradient, is usually observed in deep lakes. However, although WSPs have small depths, their high turbidity provides favourable conditions for the occurrence of this phenomenon, mainly during summer. During that time of the year, the layers nearest to the surface concentrate a larger amount of thermal energy compared to the deeper layers, which results in a temperature difference between the surface and the bottom of the pond. As a consequence a density profile appears, with the less dense layers located at the surface of the pond and the densest ones close to the bottom [5]. This stratification in the water column induces alterations in the flow pattern and a decrease of the useful volume of the pond (5). Some researchers [6,7] believe that stratification aids the development of a high pH zone and increases short circuiting which has the risk of shortening the pond retention time [8].

The importance of studying stratification and mixing in WSPs are numerous, it helps in understanding the WSPs better and aids in formulating a more realistic model. The existence of stratification in ponds has much implication on several aspects of pond design, sampling and operation. Depth effect can no longer be ignored comfortably. Besides, stratification affects the physicochemical and biological processes taking place in the pond and the transport of materials between layers. It affects the type and quality of algae in ponds, causes non-uniform oxygen distribution, and may create anaerobic conditions at the bottom layer of the pond. With the new interest in deeper ponds which is motivated by the need to reduce the large land requirement of ponds, greater attention is directed to the effect of stratification on ponds performance.

Practically, however, since ponds as shallow as 0.2m deep do stratify [9, 10] the question arises about how the problem of thermal stratification in ponds could be solved. Over the years, considerable research in WSP operation has led to the development of a number of models used to describe the hydraulic regime and predict treatment efficiency. Models range in complexity from plug or completely mixed simplifications to computational fluid dynamics (CFD)s models which are able to predict flow hydraulics at a local level [11-19]. But actual pond studies on stratification (4, 5, 20) and stratification modeling are few [21-23]. The available models do not account fully for stratification [21, 22] or simulated it using several input variables [8,23, 24].

Therefore, this research is aimed at developing a simple mathematical model which incorporates the phenomena of mixing and variation of stratification with depth. Verification of the proposed model is based on data obtained from laboratory study and waste stabilization pond at the University of Nigeria, Nsukka, Nigeria [21].

MATERIAL AND METHODS

This study involved field and laboratory investigation of the effect of stratification on WSP. The samples for the experimental work were collected from the first of a two facultative pond system in series, measuring 120m by 30m by 0.2m, which received effluent from an imhoff tank.

The physicochemical parameters observed were temperature, dissolved oxygen, pH, COD, BODs, nitrates, total phosphorous, suspended solids, algal concentration, organic loading and coliform bacteria per 100m!. The experimental set up consisted of six rectangular units made of thick metal sheets. One of the rectangular units was operated under control condition while the other five were operated under varying temperature conditions.

The LSWSP inlet were connected to a flow inducers to obtain a constant influent flow. Feed lines of 19mm diameter (PVC) pipes with 19mm diameter gate valves to regulate the influent flow were connected from the ponds to the 500L polythene vessel capacity feed tank with a tee joint to enhance even distribution between all the ponds.

Two 500L polythene vessels with a stirrer was used as the feed tank to which feed lines were connected to facilitate continuous operation of the system. The feed tanks were placed at an elevation of 2m and 1.5m with the ponds to enable the wastewater enter the tanks through gravity and also to allow the influent drop freely into all the ponds to facilitate dispersion within the ponds. The effluent discharged through a 19mm diameter PVC pipe fitted with a 19mm diameter gate valves to minimize back flows. The experiments were conducted inside the sanitary laboratory of the Department of Civil Engineering, University of Nigeria, Nsukka. Illumination was accomplished by providing a set of fluorescent bulbs fitted to a wooden stand. The system was set up for a few weeks to allow for the attainment of steady state conditions.

Laboratory investigation of thermal stratification in LSWSP were conducted by fixing thermostatically control heaters at the top layers of the Tanks C, D, E, and F which resulted in the heating of the surface layers when while the bottom layers remained colder. The water samples were collected at 0.1 m intervals in all the six Tanks using vertical column sampler and analysed for different parameters. All analyses were undertaken according to the methods described in the standard methods for the examination of water and wastewater [25]. The vertical profile of the experimental set up is shown in Figure 1.

MATHEMATICAL MODEL FOR THERMAL STRATIFICATION

The derivation follows the procedure used by Agunwamba [24] but differs in terms of the basic assumption made for the each sub-layer. Whereas Agunwamba [24] assumed plug flow, completely mixed flow regime is assumed in the present study. It is expected that as the pond becomes more shallow, more complete mixing rather than plug flow is achieved. The depth should influence the level of vertical mixing more just as the length to width ratio should affect the nature of plug flow.

The pond is assumed to have been stratified into M-main layers and one such layer is discretized into n-sub-layers with thicknesses h_1, h2... , h_n; bacterial populations N_1, N_2, … , N_n; dispersion numbers δ_1, δ_2…, δ_n; and volume V_1, V_2, …V_n (8). It is assumed that each layer approximates a completely mixed flow condition.

Consider a series of super-imposed stratified liquid layers occurring in pond as shown in figure 2.

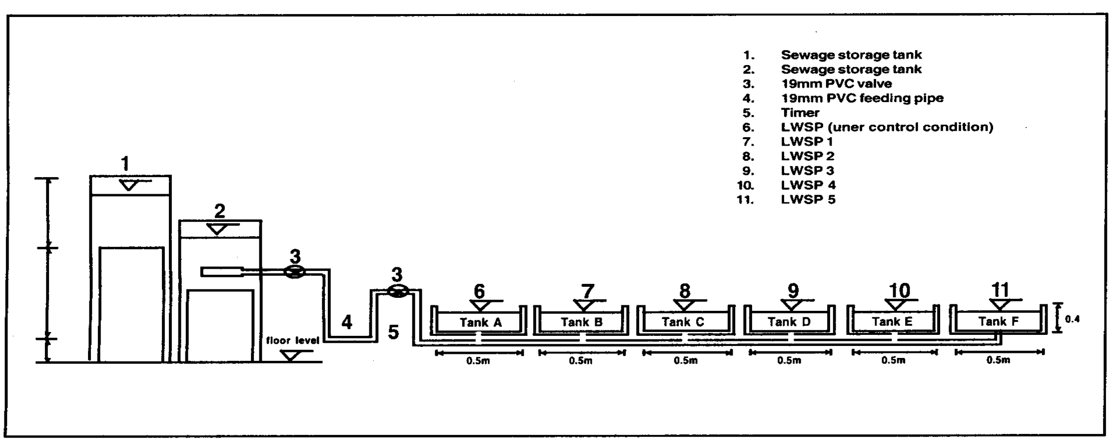

Fig. 1: *Vertical profile of LWSP for the study of thermal stratification.*

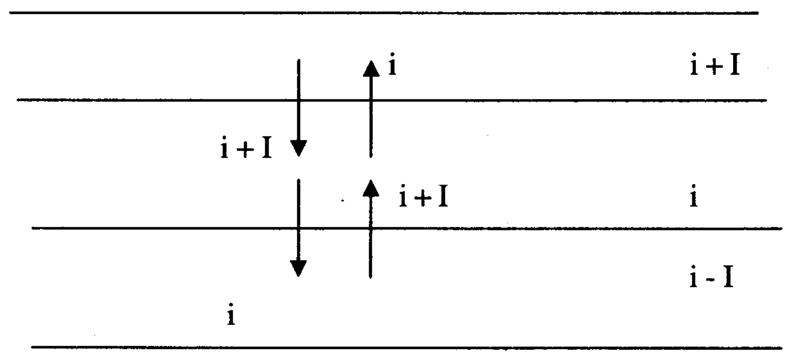

Figure 2: *Series of super-imposed liquid layers occurring in WSP.*

The population of bacteria across the interface from ith to i+ith sub-layer per unit area of the interface is described by the diffusion relationship:

$$- N_T = a_i (N_i - N_{i+1}) \quad (1)$$

Similarly, the movement from i+ith to ith sub-layer is

$$N_T = a_i (N_i +_1 - N_i) \quad (2)$$

where $a_i = \frac{\delta_i}{\theta_i}$ (3)

and the parameters OJ and 8_j are the dispersion number and dentention time at layer i. The general expression for the completely mixed flow model is given as:

$$V_i \left(\frac{dN_i}{dt}\right)] = Q_i(N_{oi} - N_i) - K_i N_i V_i \quad (4)$$

Simplifying equation (4) gives

$$\frac{dN_i}{dt} = \frac{1}{\theta_i}(N_{oi} - N_i) - K_i N_i \quad (5)$$

The completely mixed flow model can be described by considering the rate of vertical dispersion within the pond, the die-off rate coefficient and the general hydraulic characteristics of the system as:

$$\frac{dN_i}{dt} = \frac{1}{\theta_i}(N_{oi} - N_i) - K_i N_i + a \begin{bmatrix} Vertical \\ disperson \end{bmatrix} \quad (6)$$

If a separate equation for each sub-layer (Figure 2 is written and the termsfor bacterial dispersion between sub-layers added, the generalized equation can be described as:

$$\frac{dN_i}{dt} = \frac{1}{\theta_i}(N_{oi} - N_i) - K_i N_i + KiNi + \frac{\delta_{i-1}}{\theta_{i-1}}(N_{i-1} - N_i) + \frac{\delta_{i-1}}{\theta_{i-1}}(N_{i-1} - N_i)$$

$$for\ i = 1, 2, \_, n - 1 \quad (7)$$

and

$$\frac{dN_i}{dt} = \frac{1}{\theta_i}(N_{oi} - N_i) - K_i N_i + \frac{\delta_{i-1}}{\theta_{i-1}}(N_{i-1} - N_i)\ for\ i = n \quad (8)$$

Where $\frac{\delta_o}{\theta_o} = 0\ and\ \theta_i = \frac{V_i}{Q_i}, for\ 1, 2, --, n$ (9)

Considering steady-state conditions and simplifying equations (7 and 8) yields:

$$N_{oi} - N_i - K_i N_i \theta_i + \frac{\delta_{i-1}}{\theta_{i-1}} x\theta_i (N_{i-1} - N_i) + \frac{\delta_{i+1}}{\theta_{i+1}} x\theta_i (N_{i-1} - N_i) = 0 \ \text{for i = 1, 2, ---, n – 1} \quad (10)$$

and

$$N_{oi} - N_i - K_i N_i \theta_i + \frac{\delta_{i-1}}{\theta_{i-1}} x \theta_i (N_{i-1} - N_i) = 0 \quad \text{for i = n} \qquad (11)$$

N_i may be obtained on the basis of many assumptions, namely:

i) The bacterial population just within the pond entrance No_i is constant at a given layer, but may vary from one layer to another. This assumption admits the possible variation of No_i with depth unlike in other models [26].

ii) In any given pond, θ does not vary with depth [13,15].

iii) The thickness of each of the sub-layers is equal to h, that is $h_1 = h_2 = ... = h_n$. This may be applicable only in man-managed systems [10].

The assumption in (iii) is however, made to simplify the derivations.

Applying the condition (ii) above, equations 10 and 11 become respectively.

$$N_{oi} - N_i - K_i N_i \theta_i + \delta_{i-1}(N_{i-1} - N_i) + \delta_{i+1}(N_{i+1} - N_i) = 0 \quad \text{for i = 1, 2, - - -, n-l}$$

and

$$N_{oi} - N_i - K_i N_i \theta_i + \delta_{i-1}(N_{i-1} - N_i) = 0 \quad \text{for i = n,} \qquad (13)$$

Similar equations are written for 2,3,4,5 and 6 layers and then solved by algebric method. By mathematical induction, N; may be generalized for n - sub -layers as:

$$N_i = \frac{N_{oi}(1 + K_{i+1}\theta + \delta_i)(1 + K_{i-1}\theta + \delta_{i-2}) + \delta_{i-1} N_{oi-1}(1 + K_{i+1}\theta + \theta + \delta_i) + \delta_{i+1} N_{oi+1}(1 + K_{i-1}\theta + \delta_{i-2})}{(1 + K_i\theta + \delta_{i-1} + \delta_{i-1})(1 + K_i\theta + \delta_{i-2}) x (1 + K_i\theta + \delta_i)} \qquad (14)$$

For i = 1, 2, ---, n-1

and

$$N_i = \frac{N_{oi}(1 + K_i\theta + \delta_{i-2}) + \delta_{i-1} N_{oi-1}}{(1 + K_i\theta + \delta_{i-1})(1 + K_{i-1}\theta + \delta_{i-2})} \quad \text{for i = n} \qquad (15)$$

The completely mixed flow condition after thermal stratification can be obtained from equation 10 and 11 respectively. During the cooling period, the pond content turn homogeneous and the bacteria dispersion between sub-layers and other parameters become equal and

$$N_{i+1} = N_{i-1} = N_i \qquad (16)$$

Substituting equation 16 into equations 10 and 11 gives:

$$N_i = \frac{N_o}{1 + K\theta} \qquad (17)$$

Equation 17 is an existing completely mixed flow model.

MODEL PARAMETERS

The use of equations 14 and 15 for predicting the effluent bacterial populations requires the determination of some parameters such as k, θ and δ. While 8 is obtained from equation 9, δ is given by Polprasert and Bhattarai [14] as:

$$\delta = \frac{0.362 R_e^{-0.489} W^2}{LH} \qquad (18)$$

where R_e is Reynolds number given as (24):

$$R_e = \frac{4UR}{u} \qquad (19)$$

No_i is determined experimentally by sampling in the region of the pond inlet at various depths.

Four models exist for the computation of K. The first is given by [25] as:

$$K = 2.6\,(1.19)^{T-20} \qquad (20)$$

Although this model is used frequently in design [29], K does not depend on temperature alone, but on some other factors which were included by Polprasert and Bhattarai [14] to obtain

$$\exp(K) = 0.6351\,(1.0281)^{T}\,(1.0016)^{Cs}\,(0.9994)^{0L}. \qquad (21)$$

Apart from the above formulae, other relationships have also been obtained. Saggar and Pescod (30) developed an empirical equation for the computation of K as:

$$K = 0.5(1.02)^{Tw-20}(1.15)^{PH-6}\,(0.99784)^{LS-100} \ldots\ldots \qquad (22)$$

where T_w P^H and L_s are the water temperature, hydrogen ion concentration and concentration of soluble BOD_5 loading respectively.

The pond depth effect on K has been accounted for by the model developed by Sarikaya and Saatci [31].

$$K = K_d + \frac{K_s S_o}{K_i H} \qquad (23)$$

In equation 23, all the other factors, except depth and solar radiation, are lumped into Kd and then represented as a constant. However, Kd has been found to vary widely [22], which challenges the validity of representing it as a constant in the regression analysis. Equation 23 also failed to incorporate the effects of humic substances, pH and dissolved oxygen which are important variables in the process by which light damages bacteria [32]. Besides, it gives only the overall effect of depth and not point by point variation of K with depth [24].

Each of the models above has serious limitations [24]. Until the complex interactions governing bacterial die-off in ponds are fully understood, it may be impossible to formulate an accurate K-model. In the present study, the choice of K-models employed in analysis was determined mainly by the availability of complete data on stratification and bacterial die-off parameters Equations 21 and 22 were used for this study in the determination of K values.

MODEL VERIFICATION

The model was verified with data from full waste stabilization pond [21] and laboratory- scale waste stabilization pond. Comparisons of the measured and predicted effluent coliform bacteria were presented in Figures 3 to 9 for different days. The proposed model gave high correlation coefficient (0.7000 to 0.9999), indicating that the thermal stratification model developed in this study performed with a high degree of accuracy in the prediction of the effluent coliform bacteria. Hence, the above model is a useful tool for studies on stratification and prediction of its effect on effluent quality at the design stage. However, some of the measured data (especially, Fig. 4 tanks A, C and D; Fig. 5, tanks A, C, D and E and Fig. 6 tanks A, B, C and D) did not fit the model well. This disparity may be due to errors in the models for the computations of k and δ and the assumptions underlying the derivation of the main model.

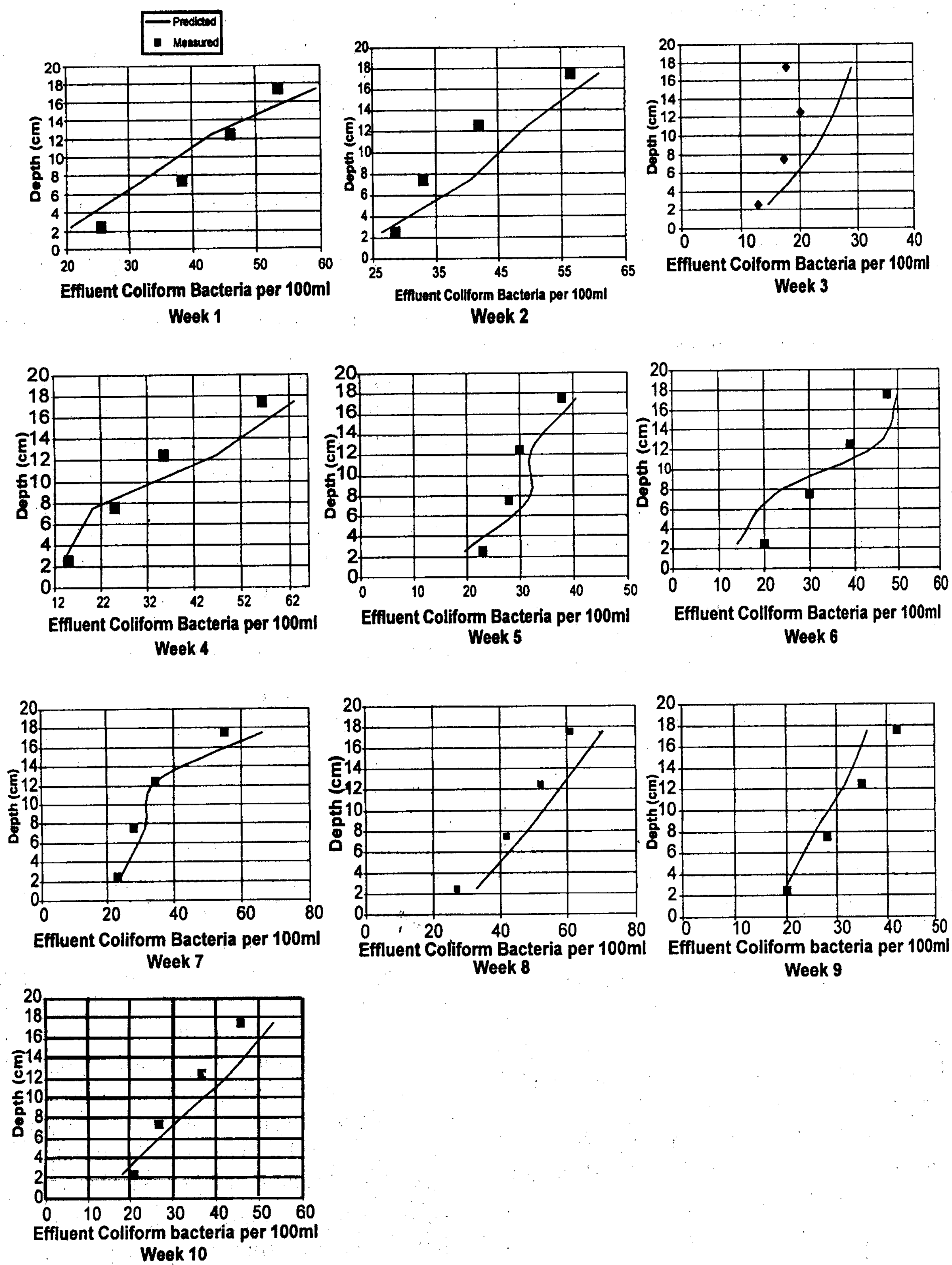

Fig. 3: Measured and Predicted effluent coliform bacteria variation with depth (Nsukka WSP) for week 1 to 10.

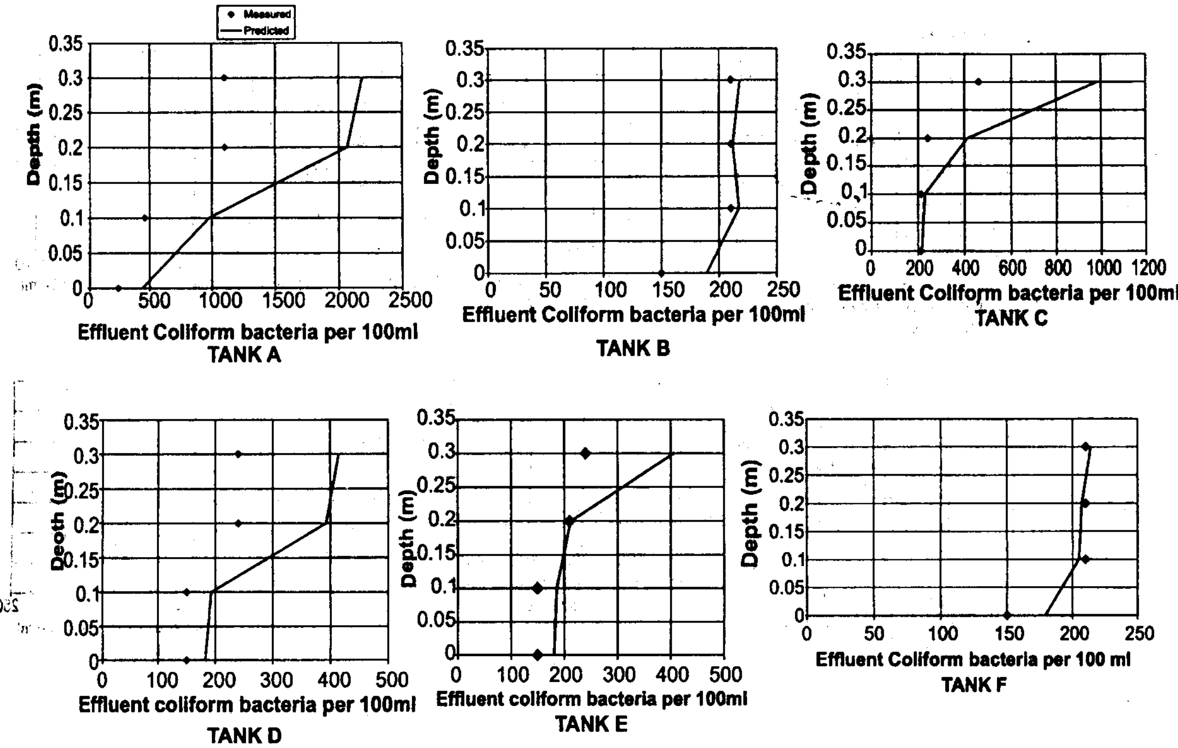

Fig. 4: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 1).

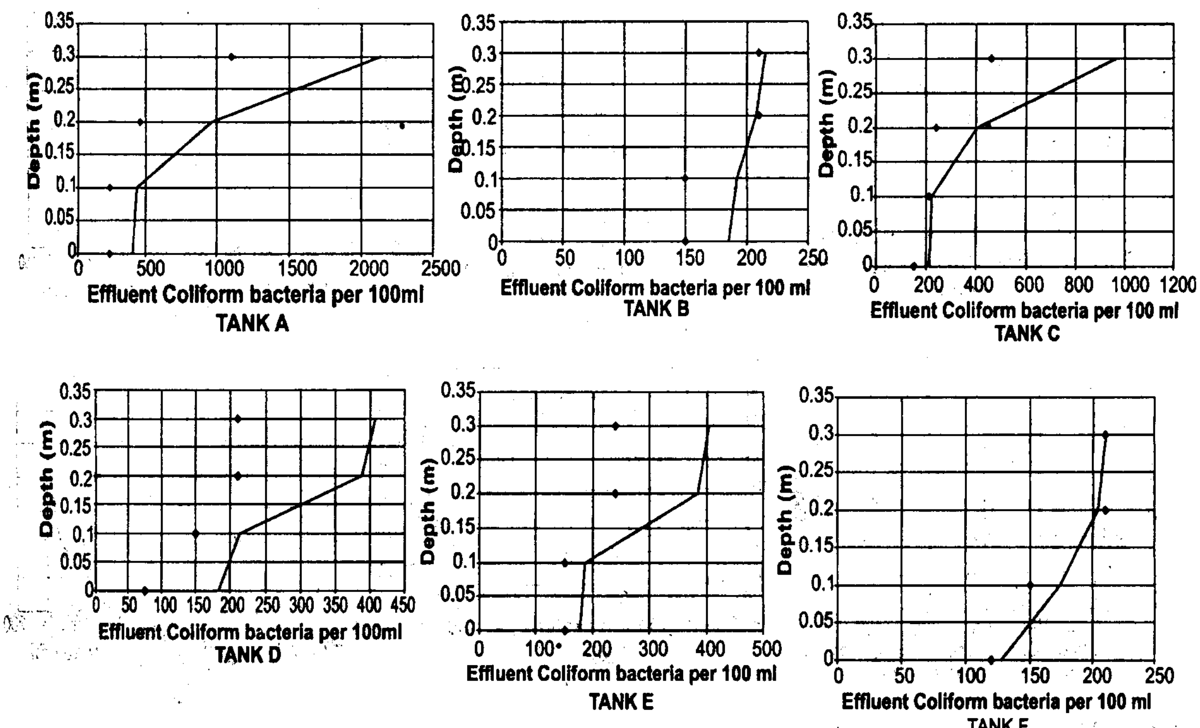

Fig. 5: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 2).

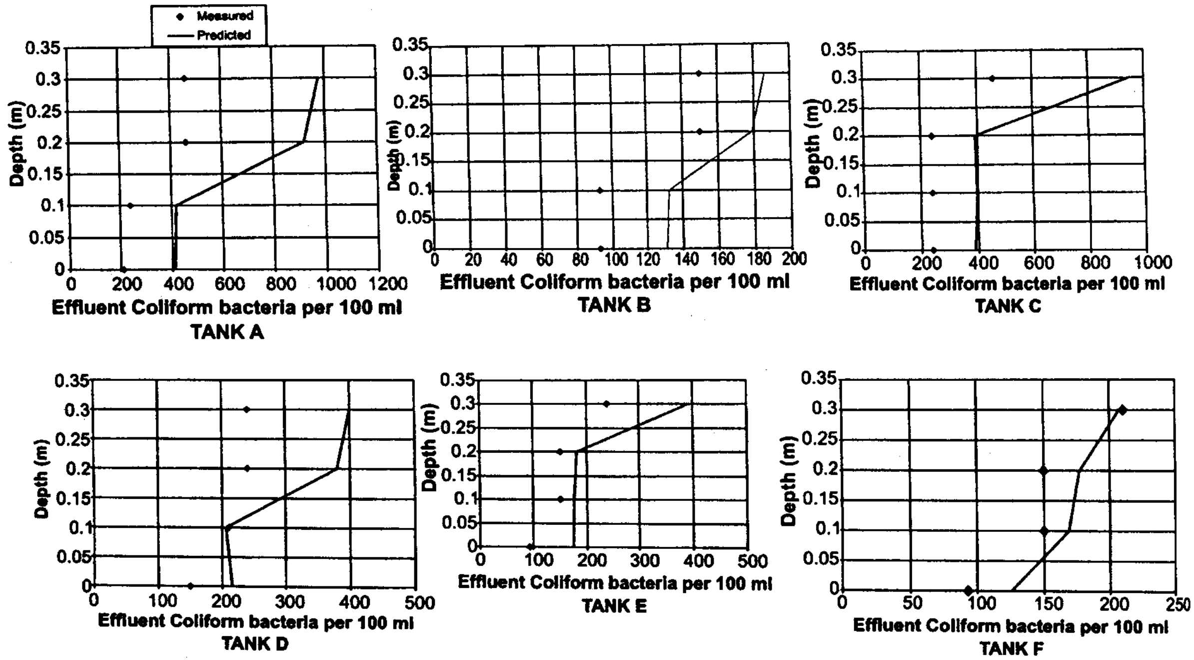

Fig. 6: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 3).

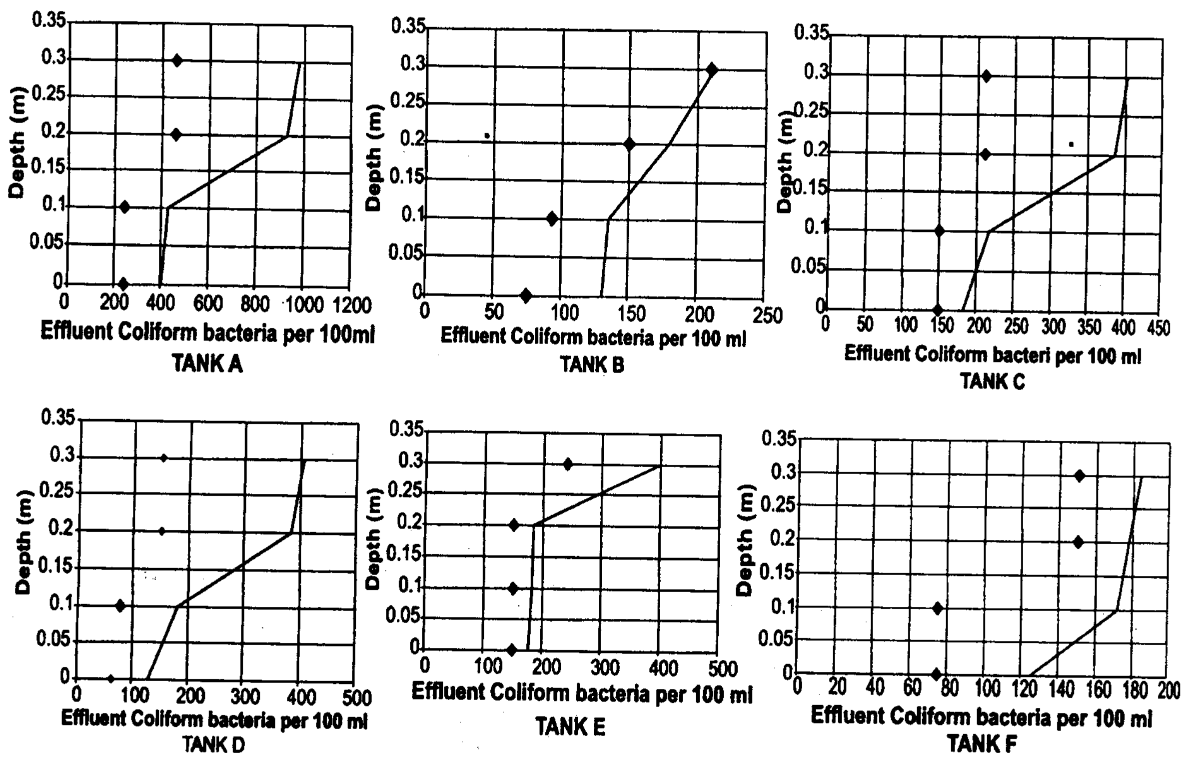

Fig. 7: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 4).

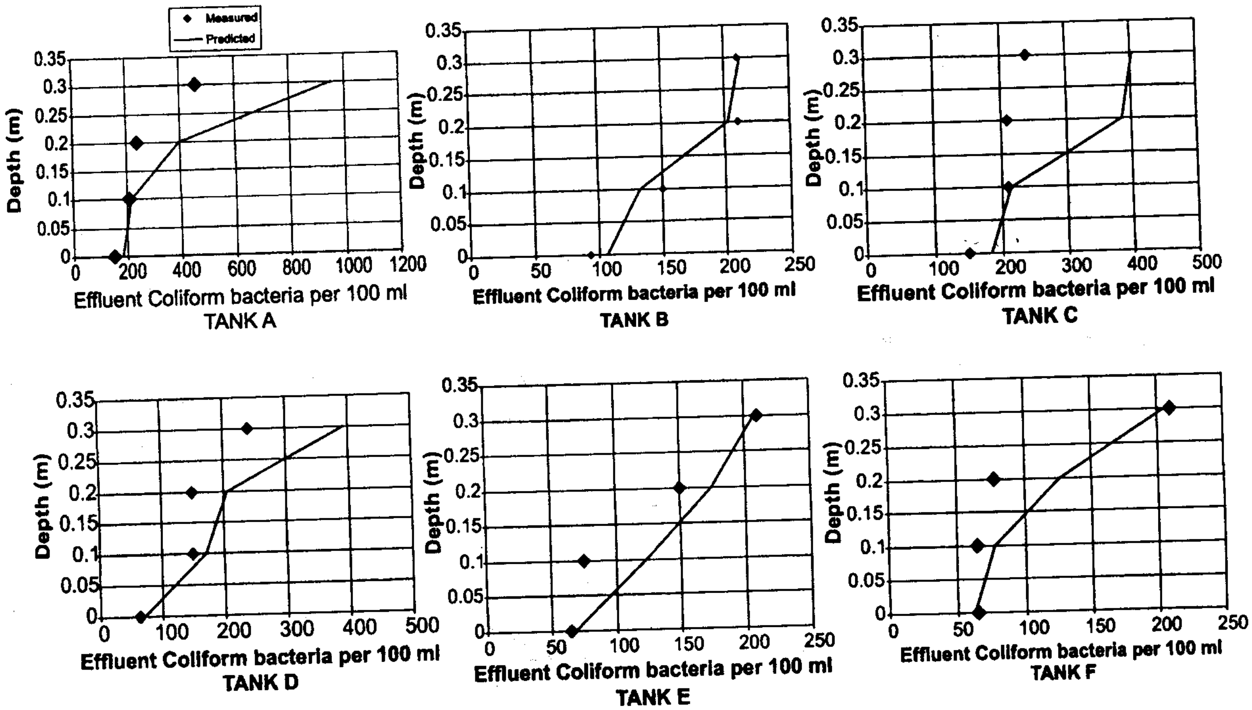

Fig. 8: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 5).

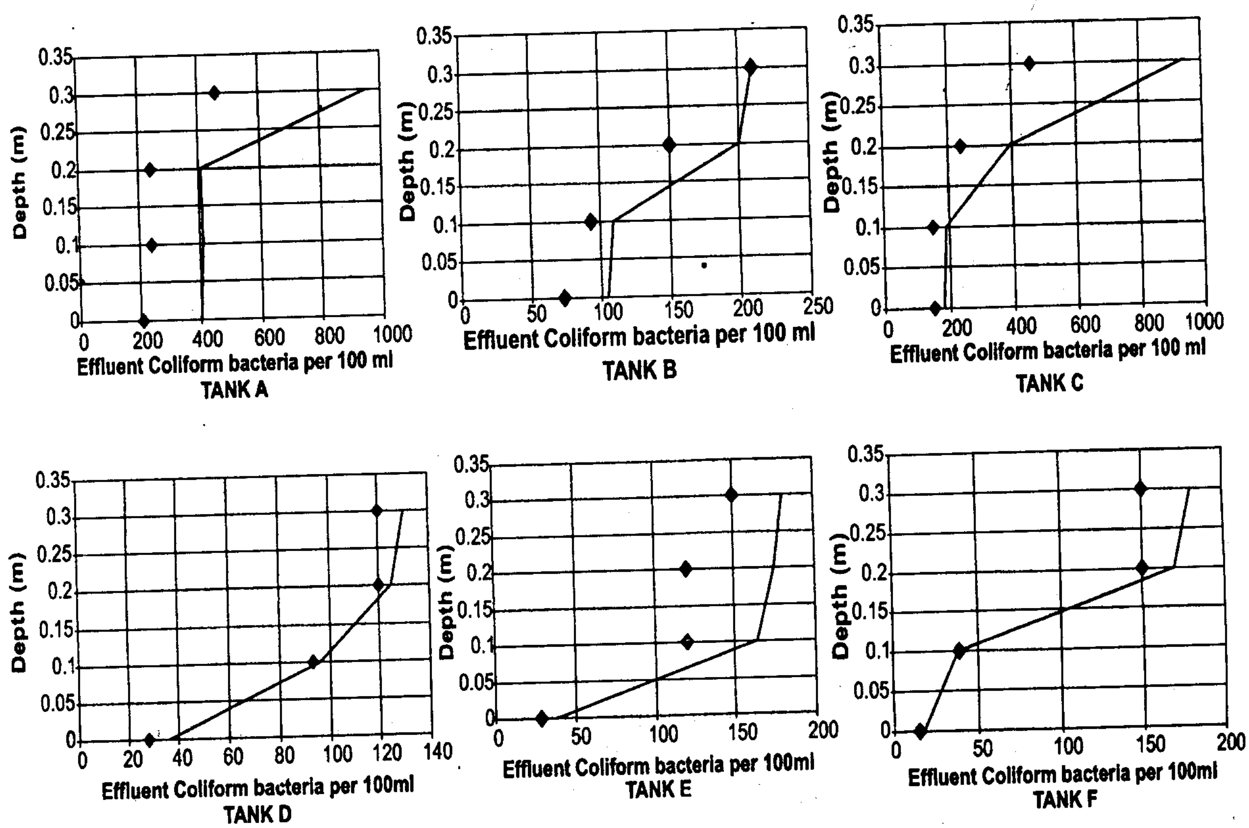

Fig. 9: Measured and Predicted effluent Coliform bacteria for Tank A,B,C,D,E, and F (Day 6).

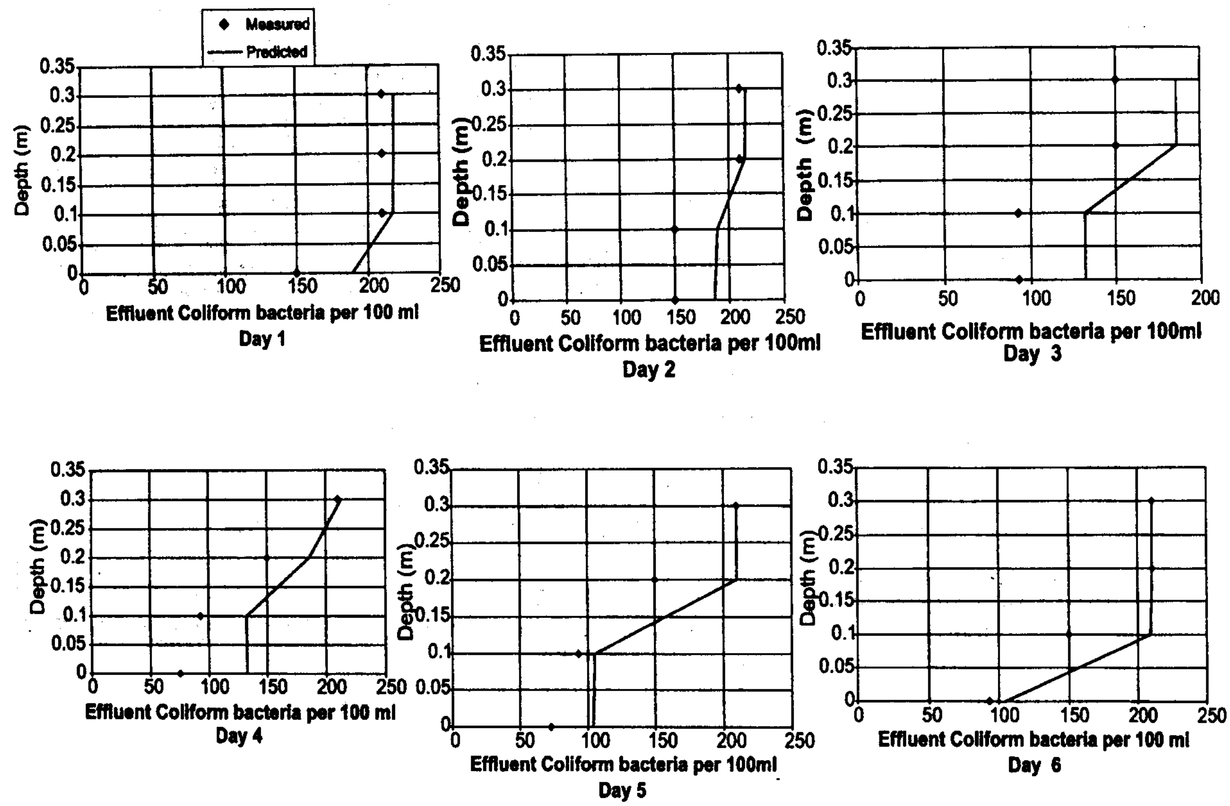

Fig. 10: *Measured and Predicted Effluent Coliform bacteria for tank B with heater at the bottom.*

CONCLUSIONS

The thermal stratification model for predicting effluent coliform number at various depths in WSPS was found as equations 14 and 15.

$$N_{oi}(1 + K_{i+1}\theta + \delta_i)(1 + K_{i-1}\theta + \delta_{i-2}) + \delta_{i-1}N_{oi-1}(1 + K_{i+1}\theta + \theta + \delta_i)$$

$$N_i = \frac{+\delta_{i+1}N_{oi+1}(1+K_{i-1}\theta+\delta_{i-2})}{(1+K_i\theta+\delta_{i-1}+\delta_{i-1})(1+K_i\theta+\delta_{i-2})x(1+K_i\theta+\delta_i)}$$

for i = 1, 2, ---, n-1

and

$$N_i = \frac{N_{oi}(1+K_i\theta+\delta_{i-2})+\delta_{i-1}N_{oi-1}}{(1+K_i\theta+\delta_{i-1})(1+K_{i-1}\theta+\delta_{i-2})} \qquad \text{for } i = n$$

and when stratification disappears, the above equations become the completely mixed flow model developed by Marais as:

$$N_o = \frac{N_e}{1 + K\theta}$$

The model was obtained by formulating a system of n equations and solving it through algebraic method. Vertical mixing between adjacent layers was accounted for by the inclusion of a dispersion term in each of the n equations. With data from the full-scale waste stabilization pond at Nsukka and laboratory scale waste stabilization pond, it has been demonstrated that the model for thermal stratifications predicts performance of stratified WSP well in some cases.

With the new interest in deeper ponds which is caused by the need to reduce large area requirement of ponds, the thermal stratification model will be applicable in design in order to reduce the problem of short circuiting. However, some of the measured data did not fit the model very well. This calls for further work on the model.

NOTATION

a: function of K, θ and δ in the dispersion model.

a_i: ratio of dispersion number to detention time in the ith sub-layer, per day

C: algal concentration, mg/l

H Pond overall depth, m

h: thickness of ith sub-layer.
K, k_i: bacterial die-off rate coefficient, and that in the ith sub-layer, respectively, per day.
K_1: light attenuation coefficient, per m
K_d: die-off rate constant in the dark, per day
K_s : rate constant for the light-mortality term, Cm^2/cal
L: pond length,m
N_i: bacteria number in the ith sub-layer at the influent per100rnl.
N_{io}: bacteria number in the ith sub-layer at the influent per100ml.
$N_i(t)$: rate of change of bacteria number with time in the ith sub-layer, and across the interface, respectively, per day per 100ml.
OL: Organic loading, kg COD/ha/day
Q, Q_i: flow rate and that in the ith sub-layer, respectively, m^3 per day.
R: hydraulic radius, m
R_e Reynolds number
S_o daily solar radiation, Cal/cm^2/day
t: time of waste water flow, day
T: temperature, ^oC
U: flow velocity, m/day
V, V_i pond volume and that of the ith sub-layer, respectively, m^3
W: pond width, m
δ, δ_i: dispersion number, that at ith sub-layer, and at depth y, respectively.
θ, θ_i: detention time, and that at ith sub-layer, respectively, day.
U: kinematic viscosity

REFERENCES

[1] Chu, C. R, and Soong, C. K. Numerical Simulation of Wind induced entertainment in a Stable Stratified Water basin. *Journal hyd.* Res., 35 (1), 1993, pp. 45-52.

[2] Dor, I., Furer, 0., Adin, A., and Benyosef, N. Turbidity related to surface temperature in oxidation ponds: Studies toward development of a remote sensing method. *Water Science and Technology*, 27 (7-8),1993, pp. 37-44.

[3] Pedahzur, R., Nusser, A.M., Dor, L., Fattal, B., and Shuval, H.l. The effect of battle installation on the performance of a single-cell stabilization pond. *Water Science and Technology*, 27 (7-8), 1993, pp. 45-52.

[4] Torres, J.J., Solerm, A.J., and Ortuno, J.F. Hydraulic Performance of a deep stabilization pond: *Water Resources* 31(4), 1997, pp.679-688.

[5] Kellner, E., and Pires, E.C. The influence of thermal stratification on the hydraulic behaviour of waste stabilization ponds. School of Engineering of Sao Carlos, Hydraulics and Sanitary Eng. Dept, Brazil, *Water Science and Technology*, Vo1.45, No.1, 2002, pp. 41-48.

[6] Fritz, J.1., Middleton, A.C. and Meredith, D.D. Dynamic Process Modelling of Wastewater Stabilization Ponds. *Journal Water Pollution Control* Fed. 51 (11), 1979, pp.2724-2743.

[7] Soler, A., Saez, J., Llorens, M., Martinez, I., Berna, L.M. and Torrella, F. Changes in Physico Chemical parameters and photosynthetic microorganisms in a deep wastewater self- depuration Lagoon. *Water Res*. 25 (6), 1991, pp.689-695.

[8] Macdonald, R. and Ernst, A. Disinfection Efficiency and Problems Associated with Maturation Ponds. *Water Science and Technology*, 18(10), 1986, pp. 19-29.

[9] Bokil, S. and Agrawal, G. Stratification in Laboratory simulations of Shallow Stabilization Ponds. *Water Research*, 11, 1997, pp. 1025-1030.

[10] Agunwamba, J.C. Prediction of bacterial population in WSPs using multiple depth layer model, I.E. (1) *Journal- EN*, Vol.77, 1997, pp.42- 48.

[11] Finney, B. A., and Middlebrooks, E. J. Facultative Waste Stabilization Pond Design. *Journal of Water Pollution Control Federation*, Vol. 52, No.l, 1980,

pp.134-139.

[12] Arceivala, S. J. Hydraulic Modelling for Waste Stabilization Ponds, *Journal of Environmental Engineering Division*, ASCE, 109 (EEl), 1983, pp.265-268.

[13] Polprasert, C., Dissanayake, N. C. and Thanh, N. C. Bacterial die-off kinetics in waste stabilization ponds. *Journal Water Pollution Control Federation,* 55 (3), 1983, pp. 285-296.

[14] Polprasert, C. and Bhattarai, K.K. Dispersion model for waste stabilization ponds. Journal Envir. Engrg. Div., ASCE, 111 (1), 1985, pp.45-59.

[15] Agunwamba, J.C. Dispersion Modelling of Waste Stabilization Pond. Ph.D Thesis, Department of Civil Engineering, University of Nigeria, Nsukka, Nigeria, 1992.

[16] Salter, H.E., Ta C.T., Ouki, S.K. and Williams, S.C. Three-dimensional Computational Fluid dynamic modelling of a Facultative Lagoon. *Water Science and 'technology*, 42 (10-11), 2000, pp.335-342.

[17] Thirumurthi, D. Design Criteria for Waste Stabilization Pond. *Journal Water Pollution Control Fed.*, Vol. 46(9), 1974, pp.2094-2106.

[18] Thirumurthi, D. Design Principle of Waste Stabilization Ponds. Journal Sanit. Eng. Div., Proc. Amer. Soc. of Civil Eng., 95, No.SAZ, Proc. Paper, 6515, 1969,p.311.

[19] Ruochuan, G. and Heinz, G. Stratification Dynamics in Wastewater Stabilization Ponds. *Water Research*, 29(8), 1909-1923.

[20] Sarikaya, H.S., Saatci, A.H., and Abdulfattah, A.F. Effect of Pond depth on Bacterial die-off. *Journal Envir.* Engrg. Div., ASCE, 113 (6),1987, pp.l350-1361.

[21] Mayo, A.V. Effect of pond depth on bacterial mortality rate. Journal of Envir. Engnr. Division, ASCE, 115(5), 1989, pp. 964-977.

[22] Moreno, M.D., Soler, A., Saez, J. and Moreno- Clavel, J. Thermal Simulation of Deep Stabilization Ponds Trib. Cebedean 497(37), 1984, pp.403-410.

[23] Llorens, M., Saez, J., and Soler, A. Influence of thermal stratification on the behaviour of a deep wastewater stabilization pond: Water Resources 26 (5),1992, pp. 569-577.

[24] Agunwamba, J.C., Ochonoger, A. and Ukpong, E. C. Experimental and Principal Component Analysis of Waste Stabilization Pond, *Journal of Applied Science and Technology*, 3(1), (In press),2003.

[25] APHA. Standard methods for the Examination of Water and Wastewater, 20th edition, Washington D. C. American Public Health Association, 1998.

[26] Wehner, J.F. and Wilhelm, F.H. Boundary Conditions of Flow Reactor, *Chemical Engineering Science,* 6,1956, pp. 89-92.

[27] Webber, N. B. Fluid Mechanics for Engineers, Chapman and Hall, London, 1976.

[28] Marais, G.V.R. Faecal Bacterial Kinetics in Stabilization Ponds. *Journal of Environmental Engineering Division, ASCE,* Vol. No.1, 1974, pp.119-129.

[29J Mara, D.O. and Pearson, H.W. Artificial Freshwater Environment. Waste Stabilization Ponds in Biotechnology, Vo1.8, pp. 179-1 84, 1986.

[30] Saggar, M.M., and Pescod, M.B. Modelling Coliform bacteria in Wastewater Stabilization. Ponds *Water Science and*

Technology, *1992*.

[31] Sarikaya, H.S., and Saatci, A. H. Bacterial die-off in waste stabilization ponds. *Journal Envu: Engrg. of. ASCE*, 113 (2),1987, pp. 66-382.

[32] Curtis, T.P., Mara, D.D., and Silva, S. A. Influence of P^H, Oxygen and Humuc substances on Ability of Sunlight to Damage Feacel Coli forms in Waste Stabilization Pond Water. *Applied Environmental Microbiology*, 58(4), 1991, pp.l335-1340.