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Model for Vertical Temperature Profile in Waste Stabilization Ponds

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ABSTRACT

Thermal stratification is a natural phenomenon which occurs in waste stabilization ponds caused by vertical temperature difference which alters the flow patterns in the ponds, affects its performance and design, thereby reducing the efficiency of its operation. This study therefore developed a mathematical model for predicting the vertical temperature profile in WSPs. The solution of the model was obtained using a numerical solution method based on a fourth order Runge-Kutta method. The results were verified with data from several field ponds at different depths. Maximum difference of 19.05% between the calculated and predicted temperature profiles were obtained as shown in the Figures. The coefficients of correlation between the measured and the predicted values range from 0.6774 to 0.9990 as calculated.

KEYWORD: *Thermal stratification, model, temperature profile, Runge- Kutta and waste stabilization ponds.*

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I. INTRODUCTION

Waste stabilization ponds (WSPs) are now regarded as the method of first choice for the treatment of wastewater in many parts of the world. In the United States, one third of all wastewater treatment plants are waste stabilization ponds serving populations upto 5000 as reported by (EPA, 1983; Boutin and others, 1987; and Bucksteeg, 1987) have also reported that wastewater stabilization pond are very widely used in small rural communities in Europe with population close to 2000. Larger systems exist in Mediterranean France and also in Spain and Portugal. However, in warmer climates (the middle East, Africa, Asia and Latin America) ponds are commonly used for large populations upto one million (Soares and others, 1996).

In the developing countries and especially in the tropical and equatorial regions, sewage treatment by wastewater stabilization ponds has been considered an ideal way of using natural processes to improve sewage effluent. The importance of waste stabilization ponds is well documented in the literature (Maraise, 1974; Mara and others, 1983; and Polprasert and Others, 1983). Its economic advantage over the conventional technologies and the abundance of sunlight and prevalent high ambient temperature in the tropical and subtropical regions, have made it so popular. The parameters used in judging the performance of wastewater stabilization ponds are bacteria rate of degradation, biochemical oxidation, dispersion, bacteria die-off rate and thermal stratification which are influenced by temperature gradient. Many models (Polprasert and others, 1983; Marais and others, 1961; Bowles, 1979; Klock, 1971; and Thirumurthi, 1969) have been proposed to describe the process of bacterial degradation, but none has been found acceptable. The fact that the largest relative difference in temperature appears close to the surface layer of the pond during thermal stratification processes can be related to the complex mechanisms of thermal energy transfer between the water surface and air. In this zone, wind gusts and surface waves play significant role in the transfer mechanisms but owing to their random behaviour it is difficult to predict their effects correctly.The phenomenon of thermal stratification, overturning of density stratification and complete mixing are natural processes which are rampant during summer.

The values and distribution of temperature in a mass of water play a fundamental role in the behaviour of these systems due to the following factors:

[1] Physicochemical and biological processes depend greatly on temperature values and
[2] The mixing phenomena are closely related with the thermocline, because it restricts the heat and matter transport between the different layers defined in the water column as a consequence of thermal stratification.

As in other water bodies (lakes, reservoirs, etc), the thermal stratification of a deep pond begins in spring and, starting from a homogeneous temperature, a stratification starts developing such that it eventually results in a well-defined thermocline. This thermocline separates two clearly differentiated layers: an aerobic superior one (epilimnion) and anaerobic inferior one (hypolimnion). This situation remains until when the surface cooling provokes a gradual deepening of the thermocline till isothermicity is re-established. This gradual deepening throughout the cycle causes the nutrient rich water of the hypolimnion to ascend to the surface layer that has become depleted as a result of the intense biochemical activity favoured by the higher temperature, the presence of solar radiation, and the photosynethetic and surface oxygenation. On the other hand, the biomass generated in the epilimnion settles down and, once its mineralization takes place, it constitutes an additional contribution of nutrients to the hypolinion (Moreno, 1983; Schertzer and others, 1987; Simons and others 1987 and Soler and others, 1991).Stratification can be caused by temperature differences. Hence, the objective of this paper is to present a mathematical model for the prediction of vertical temperature profile in ponds. The model will be solved using Runge-Kutta method and verified with literature data (Silva, 1982; Vidal, 1983; Agunwamba, 1997; Moreno-Grau and others, 1983 and Kellner and Pires, 2002).

In the determination of the thermal flux provided by solar radiation and the air was primarily a function of the latitude of the pond site, the distance between the earth and the sun (varying along the year), the temperature of the air and the fraction of the cloud cover. The calculation of the thermal flux can be found in full detail in (Pires and Kellner, 1999 and Mayo, 1989). Although the approach by (Fritz, Meredith and Middleton 1980) was complicated, this study therefore tried to simplify their work by using Kreyszig (1993) who developed the rate constant equation based on solar radiation, the pond depth and a constant depending on the season of the year.

II. METHODOLOGY

In order to verify the quality of the model, its results were compared with experimental data from other studies based on temperature measurement. The various researchers include (Silva, 1982; Vidal, 1983; Agunwamba, 1997; MorenoGrau and others (1984). The pond studied by Silva is located in Campina Grande, para-lba, northeast Brazil (latitude 7°13 11 ≤ S), which has a hot, dry climate, with small daily temperature variations, the pond studied by vidal is located in Santa Fe do Sul, São Paulo, southeast Brazil (latitude 20° 46 0 ≤ S), an area with a higher daily temperature variation. Similarly, the pond studied by Agunwamba is located at the campus of the University of Nigeria, Nsukka in the southeastern part of Nigeria with small daily temperature variations; and the pond studied by Moreno-Grau *et al* is located at Cartagena-Spain. Silva (1982) measured the temperature variation with depth on 6-7 October 1987, in a facultative pond of length 25.70m, width 7.40m and depth 1.25m, located in Campina Grande. Vidal (1983) performed his measurements on a facultative pond in Santa Fē do Sul, with a length of 80m, a width of 66m and a depth of 1.5m. Agunwamba (1997) performed his measurements on a facultative pond in the University of Nigeria, Nsukka Campus measuring 120m length, 30m width and 0.2m deep.

III. DEVELOPMENT OF MATHEMATICAL MODEL FOR VERTICAL TEMPERATURE PROFILE IN WSP

The general expression for the material balance can be written as:

The balance of thermal energy stored in the jth element = due to horizontal movement   Solar radiation from sun   +   Local advection

–   Vertical advection   –   Energy due to mixing (dispersion) - - - - (1)

According to Kellner and Pires (2002) the balance of thermal energy in a volume element can be expressed as:

$$\frac{\partial H_j}{\partial t} = \left(h_j - ho + hsz\right) - \left(h_{wj} - h_{wj} + 1\right) - \left(h_{dj} - h_{dj} + 1\right) \qquad - \quad - \quad - \qquad (2)$$

where:

H_j	=	$C\overline{V}_j T_j$ - - - - - - -	*(3a)*
h_i	=	$CQ_j T_j$ - - - - - - -	*(3b)*
h_o	=	$CQ_O T_O$ - - - - - - -	*(3c)*
h_{sz}	=	ZA_Z - - - - - - -	*(3d)*
h_{dj}	=	$CD_Z A_Z \frac{\partial T}{\partial Z}$ - - - - - - -	*(3e)*
Z	=	*(1-)* $S_o\, e^{-K.Z}$ - - - - - - -	*(3f)*
hwj	=	$CQ_Z T_Z$ - - - - - -	*(3g)*

and

H_j	=	the thermal energy contained in the jth element (J);
C	=	the specific heat of water, $Jkg^{-10}C^{-1}$;
V_j	=	the specific mass of water kgm^{-3};
T_j	=	temperature in element j ^oC;
A_z	=	the direct insulation J sec^{-1};
h_i	=	the thermal energy introduced by the influent flow J sec^{-1};
h_o	=	the thermal energy removed by the effluent flow, J sec^{-1}
h_{sz}	=	the direct insulation, J Sec^{-1};
Z	=	the flow of solar radiation at depth Z, $Jm^{-2}S^{-1}$
S_o	=	the radiation rate absorbed in the liquid surface, Cal m^{-2} day^{-1};
h_{dj}	=	the heat transferred by diffusion along the vertical axis, JS^{-1}
h_{wj}	=	the heat adverted along the vertical axis;
D_z	=	the coefficient of vertical dispersion (m^2S^{-1}) that comprises molecular and turbulent diffusions
K	=	the coefficient of light attenuation, m^{-1}.

By substituting equations (3a) to (3g) into equation (2) yield the following results:

$$\frac{\partial\left(C\overline{V}_j T_j\right)}{\partial t} = \left(CQ_{ij}T_{ij} - CQ_{oj}T_j + zA_z\right)$$
$$-\left(CQ_{zj}T_j - CQ_{zj+1}T_{j+1}\right)$$
$$-\left(CD_jA_j\frac{\partial T}{\partial Z}\bigg|_j - CD_{j+1}A_{j+1}\frac{\partial T}{\partial Z}\bigg|_{j+1}\right) \qquad - \quad - \quad - \quad - \quad - \qquad 4$$

The specific heat of water (C) is a constant and will cancel, out and equation (4) becomes:

$$\frac{\partial\left(\overline{V}_j T_j\right)}{\partial t} = \left(Q_{ij}T_{ij} - Q_{oj}T_j\right) + \frac{Z}{C}A_Z$$
$$-\left(Q_{zj}T_j - Q_{zj+1}T_{j+1}\right)$$
$$-\left(D_jA_j\frac{\partial T}{\partial Z}\bigg|_j - D_{j+1}A_{j+1}\frac{\partial T}{\partial Z}\bigg|_{j+1}\right) \qquad - \quad - \quad - \quad - \quad - \qquad 5$$

The impact of solar radiation is on the entire parameters in the pond such as temperature, specific heat of water (C), and the direct insulation (A). Thus, equation (5) gives:

$$\frac{\partial\left(\overline{V}_J S_o T_j\right)}{\partial t} = \left(Q_{ij}S_oT_{ij} - Q_{oj}S_oT_j\right)$$

$$+\frac{1}{CS_o}S_o z S_o A_z - \left(Q_{zj}S_oT_j - Q_{zj+1}S_oT_{j+1}\right)$$

$$-\left(D_jS_oA_jS_o\left.\frac{\partial T}{\partial Z}\right|_j - D_{j+1}S_oA_{j+1}S_o\left.\frac{\partial T}{\partial Z}\right|_{j+1}\right)$$

Thus, equation (6) can be related to the general word expression of equation (1). Therefore, after simplification and discretization, equation (6) becomes:

$$\frac{\partial T_j}{\partial t} = \frac{1}{\bar{V}_j}\left(Q_{ij}T_{ij} - Q_{oj}T_j\right) + \frac{1}{V_j}CS_oZS_oA_j$$

$$-\frac{1}{\bar{V}_j}\left(Q_{zj}T_j - Q_{zj+1}T_{j+1}\right) - \frac{1}{\bar{V}_j}\frac{D_jS_oA_jS_oT_{j+1}}{Z}$$

$$+\frac{1}{\bar{V}_j}\frac{D_jS_oA_j}{Z}S_oT_j + \frac{1}{\bar{V}_j}\frac{D_{j+1}S_oA_{j+1}}{Z}S_oT_j$$

$$+\frac{1}{\bar{V}_j}\frac{D_{j+1}S_o}{Z}A_{j+1}S_oT_{j+1} \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 7$$

The solution to the partial differential equation give by equation (7) can be obtained by (Kreyszig, 1993; Micolescus, 1974 and Stroud, 1996) have given the basic numerical solution of the partial differential equation.

Therefore for the temperature increment a fourth order Runge-Kutta method will be applied as given in equation (8) thus:

$$T_j^{t+1} = T_j^t + \frac{1}{2}\frac{t}{6}\left\{S_oO_{l,j} + 2S_oO_{2,j} + 2S_oO_{3,j} + O_{4,j}\right\} \qquad - \quad - \quad - \quad - \qquad 8$$

where:

$$O_{l,j} \quad = \quad f\left(T_j^t\right) \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 9a$$

$$O_{2,j} \quad = \quad f\left(T_j^t + \frac{1}{2}tO_{1,j}\right) \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 9b$$

$$O_{3,j} \quad = \quad f\left(T_j^t + \frac{1}{2}tO_{2,j}\right) \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 9c$$

and

$$O_{4,j} \quad = \quad f\left(T_j^t + \frac{1}{2}tO_{3,j}\right) \qquad - \quad - \quad - \quad - \quad - \quad - \qquad 9d$$

Equation (8) can be simplified as:

$$T_j^{t+1} = T_j^t + \frac{t}{12}S_o\left\{O_{1,j} + 2O_{2,j} + 2O_{3,j} + \frac{O_{4,j}}{S_o}\right\} \qquad - \quad - \quad - \quad - \qquad 10$$

From Mayo (1989) the rate constant K is given as:

$$K \quad = \quad 0.108 + f \times \frac{S_o}{H} \qquad - \quad - \quad - \quad - \quad - \qquad 11$$

where:

So = the solar radiation or the radiation rate aborbed in the liquid surface, $Cal/m^2/day$
H = the pond depth in meter
f = a constant depending on the season of the year

Substituting equation (11) into equation (10) gives:

$$T_j^{t+1} = T_j^t + \frac{t}{12}\left(\frac{K-0.108}{fxH^{-1}}\right)x\left\{O_{1,j} + 2O_{2,j} + 2O_{3,j} + \left(\frac{FxH^{-1}}{K-0.108}\right)O_{4,j}\right\} \quad - \quad 12$$

Hence, the final equation can be expressed as:

$$T_j^{t+1} = T_j^t + \lambda_y\left\{O_{1,j} + 2O_{2,j} + 2O_{3,j} + \delta_y O_{4,j}\right\} \quad - \quad - \quad - \quad - \quad - \quad 13$$

where

$$\lambda_y = \frac{t}{1036800}\left(\frac{K-0.108}{fxH_y^{-1}}\right) \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad 14$$

$$\delta_y = \left(\frac{fxH_y^{-1}}{K-0.108}\right) \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad 15$$

and

$$O_{1,j} = f(T_j^t) \quad - \quad - \quad - \quad - \quad - \quad 16$$

$$O_{2,j} = f\left(T_j^t + \frac{t}{172800}O_{1,j}\right) \quad - \quad - \quad - \quad - \quad - \quad 17$$

$$O_{3,j} = f\left(T_j^t + \frac{t}{172800}O_{2,j}\right) \quad - \quad - \quad - \quad - \quad - \quad 18$$

$$O_{4,j} = f\left(T_j^t + \frac{t}{172800}O_{3,j}\right) \quad - \quad - \quad - \quad - \quad - \quad 19$$

where t is the adopted time interval in seconds.

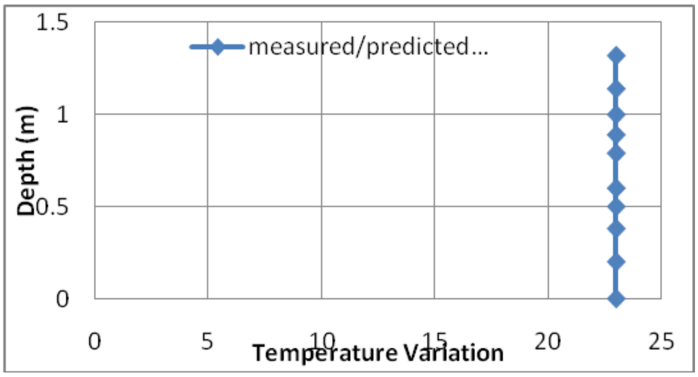
IV. DISCUSSION OF RESULTS

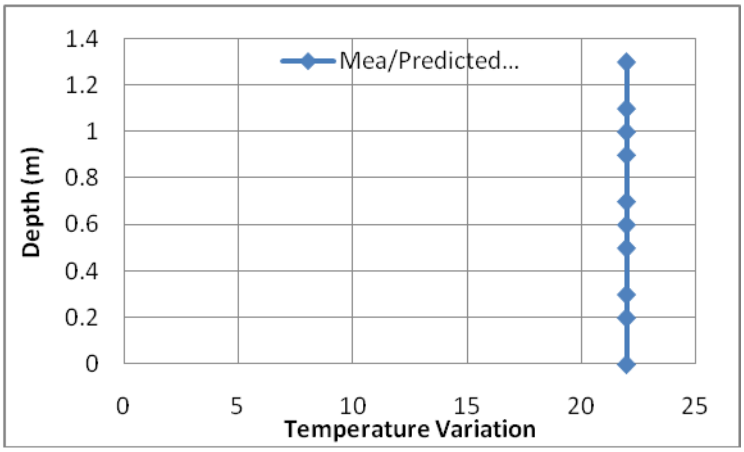
The data from several field wastewater stabilization ponds obtained from literature were used to evaluate the response of vertical temperature profile model of equation (13) developed in this study. Comparisons of the measured experimental temperature data and those predicted from the model were made to show the responses accuracy and sensitivity. The plot of predicted temperature values and measured temperature values versus depth are shown in Figures 1, 2, 3, 4, 5 and 6, respectively.Comparing the measured temperature values with the predicted values gives a maximum difference of 19.05% between the calculated and observed temperature profiles. The coefficients of correlation between the measured and the predicted values range from 0.6774 to 0.990 and the standard error of estimate ranges from 0.00315 to 0.382 indicating that the model of vertical temperature profile developed in this study performed with a high degree of accuracy.

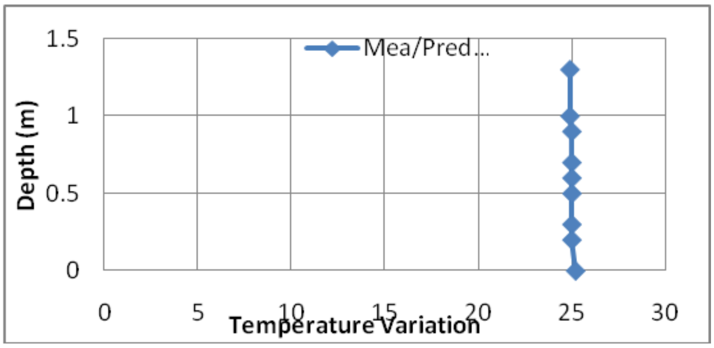
V. CONCLUSION

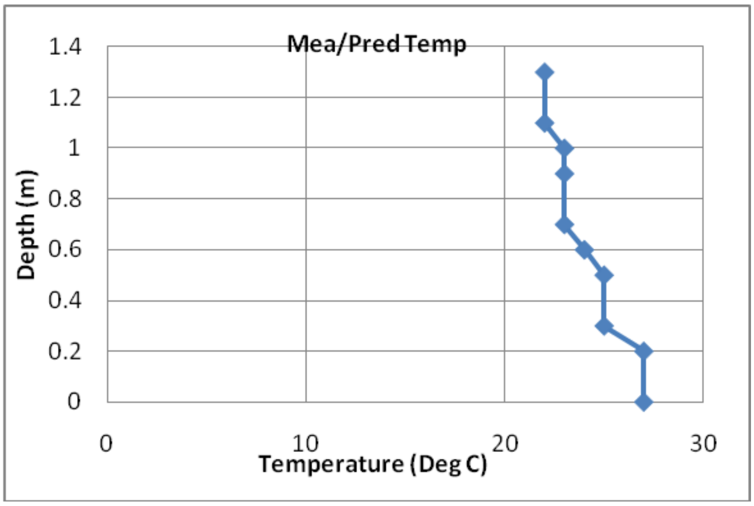
[1] The proposed model for the determination of vertical temperature profile in waste stabilization ponds developed in this study performed with a high degree of accuracy.
[2] The proposed model indicates the complete thermal cycle such as complete mixing, overturning of density stratification and thermal stratification.
[3] Complete mixing occurs when the temperature profiles are in uniform; and
[4] Thermal stratification are caused by temperature differences.

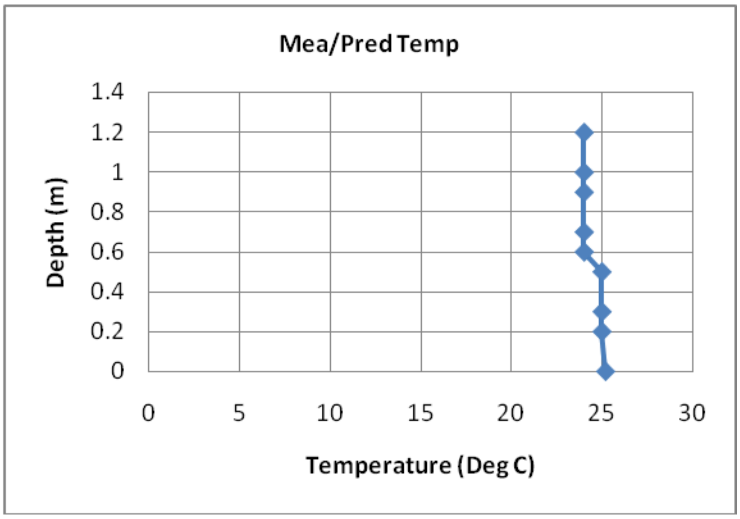
This study therefore recommends that waste stabilization pond should be sited in the direction of wind in order to reduce the temperature increase caused by heat, thereby avoiding overturning and subsequent stratification in the pond.


measured/predicted...
Depth (m)
1.5
1
0.5
0
0
5
10
15
20
25
Temperature Variation


Mea/Predicted...
Depth (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Temperature Variation


Mea/Pred...
Depth (m)
1.5
1
0.5
0
0
5
10
15
20
25
30
Temperature Variation


Mea/Pred Temp
Depth (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
Temperature (Deg C)



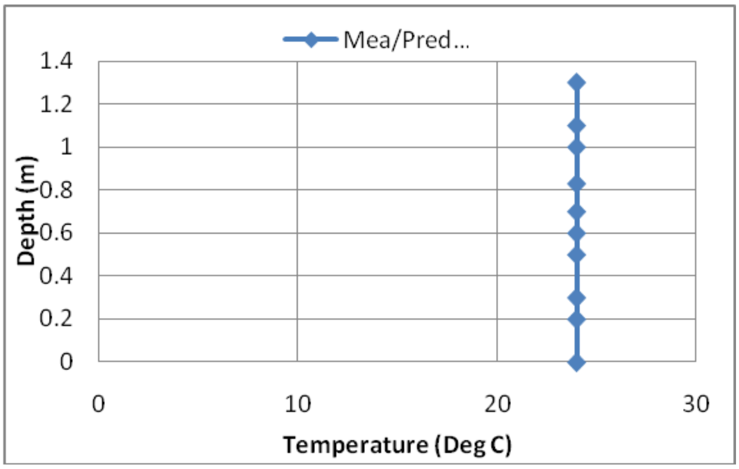
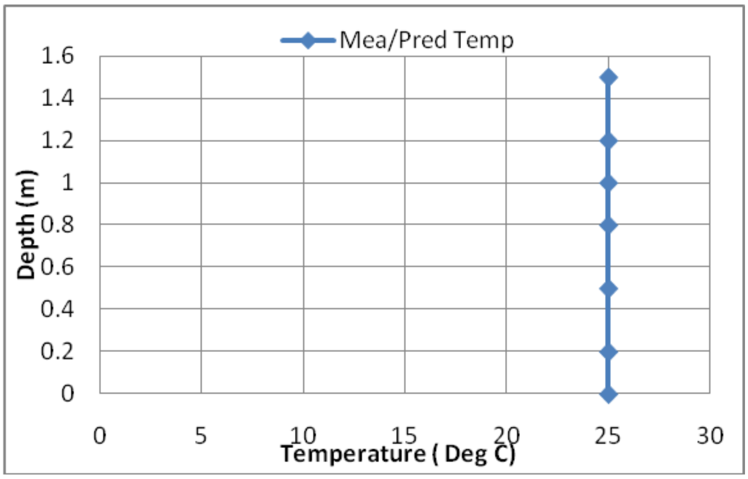
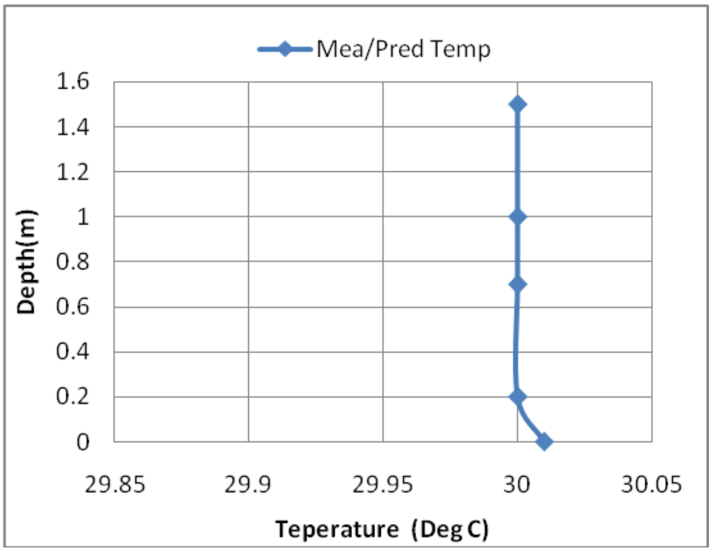
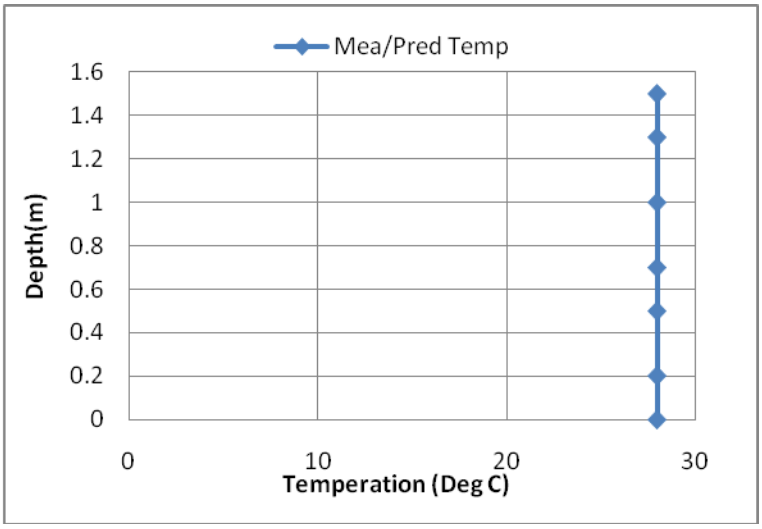
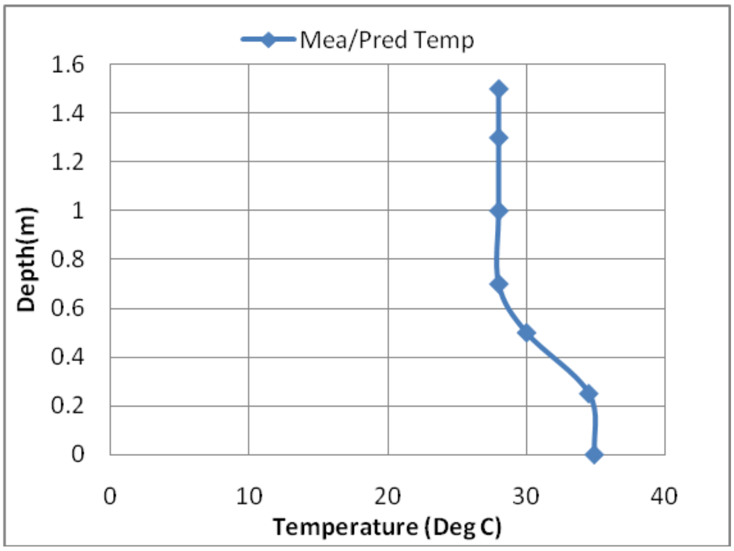


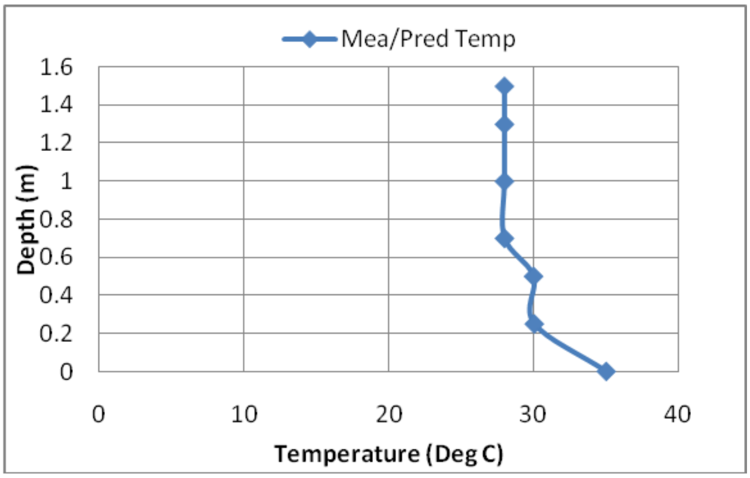
Fig.1: Measured and Predicted Temperature Variation with Depth Using Silver (1982) Experimental Data For 6:00, 10:00, 12:00, 14:00 and 22:00 Hours.




Mea/Pred Temp
Depth(m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
29.85
29.9
29.95
30
30.05
Teperature (Deg C)


Mea/Pred Temp
Depth(m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
Temperation (Deg C)


Mea/Pred Temp
Depth(m)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
Temperature (Deg C)



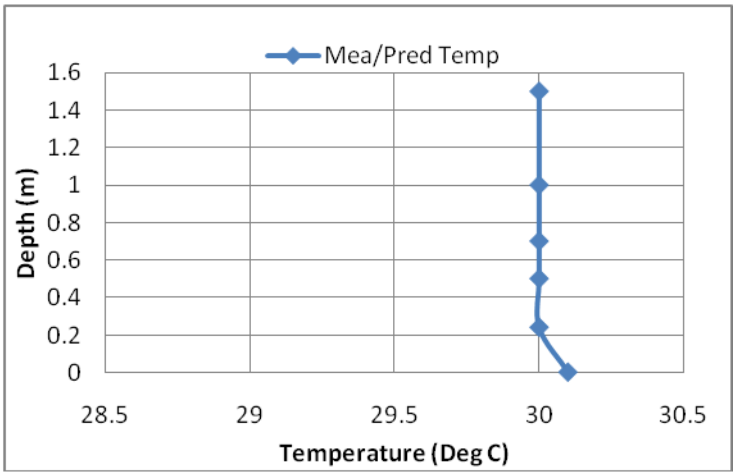
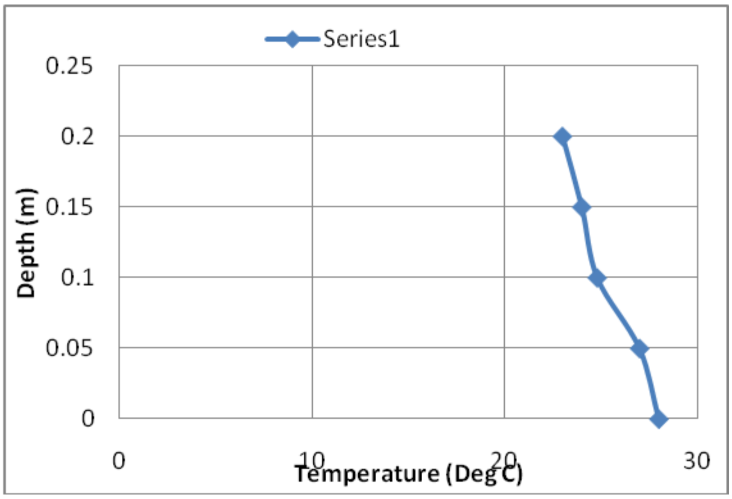
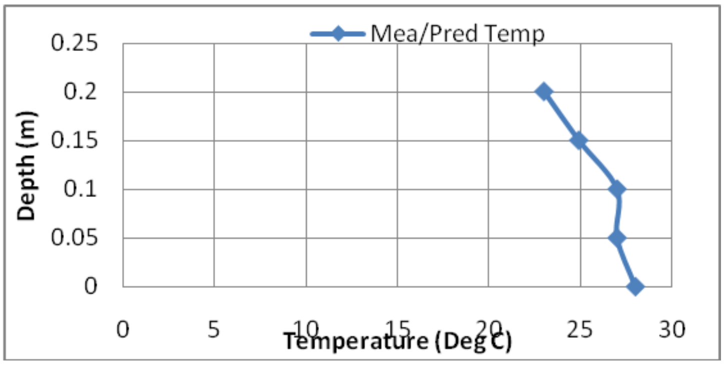
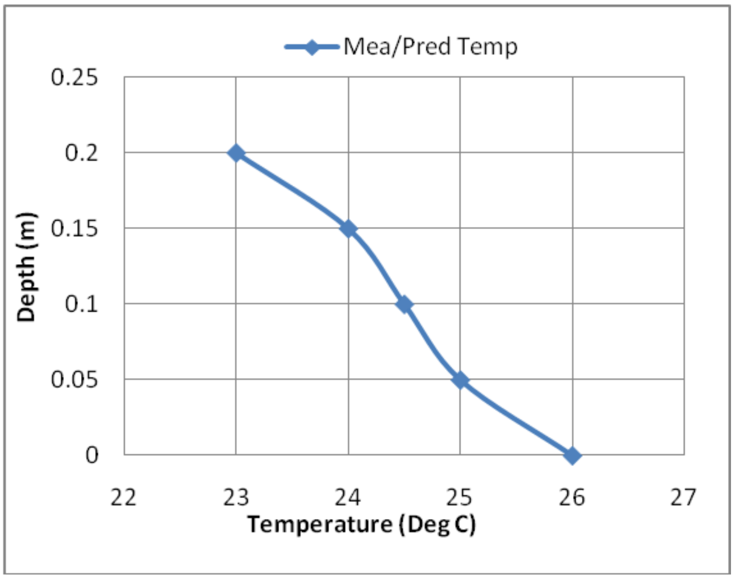
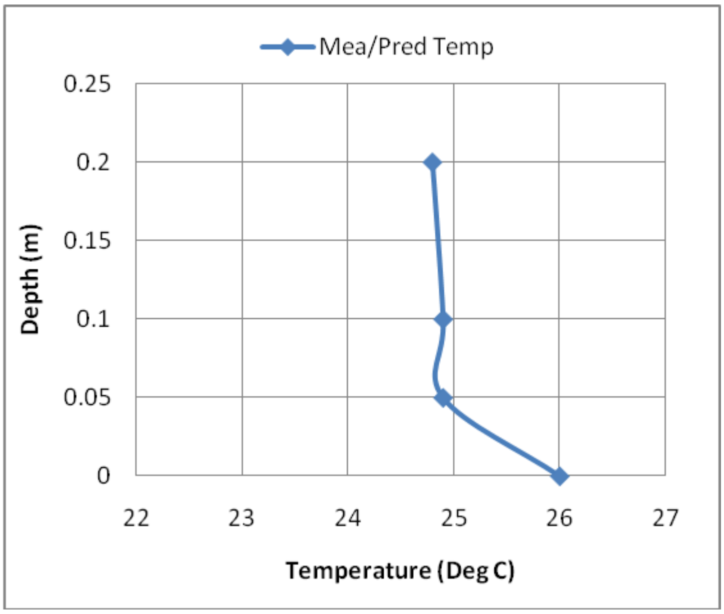


Fig.2: Measured and Predicted Temperature Variation with Depths Using Vidal (1983) Experimental Data for 6:00,10:00,12:00,14:00,16:00 and 22:00 Hours




Mea/Pred Temp
Depth (m)
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
Temperature (Deg C)


Mea/Pred Temp
Depth (m)
0.25
0.2
0.15
0.1
0.05
0
22
23
24
25
26
27
Temperature (Deg C)


Mea/Pred Temp
Depth (m)
0.25
0.2
0.15
0.1
0.05
0
22
23
24
25
26
27
Temperature (Deg C)

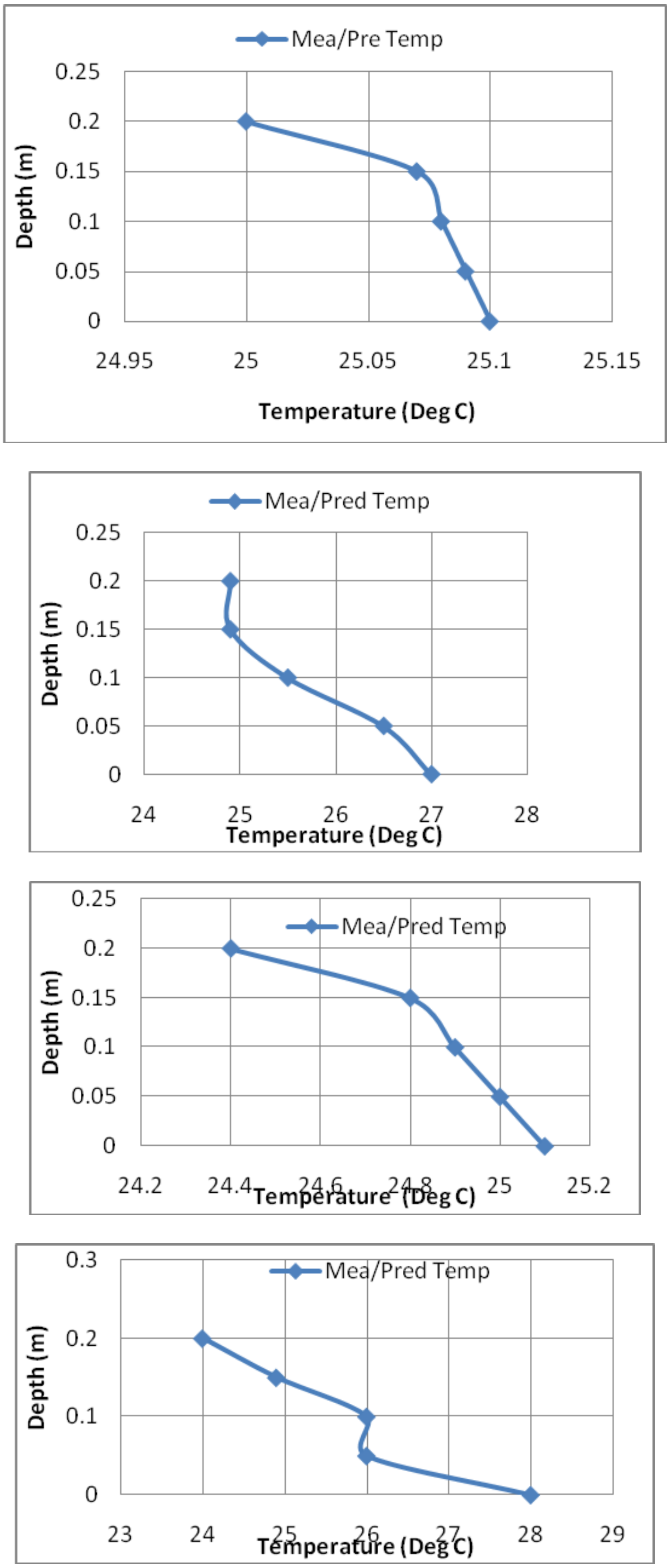
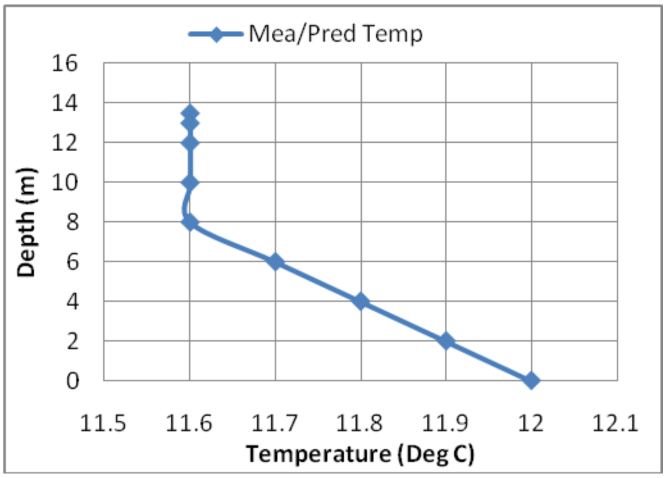
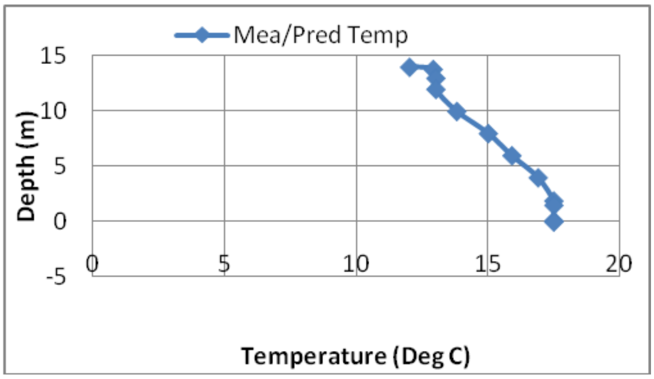
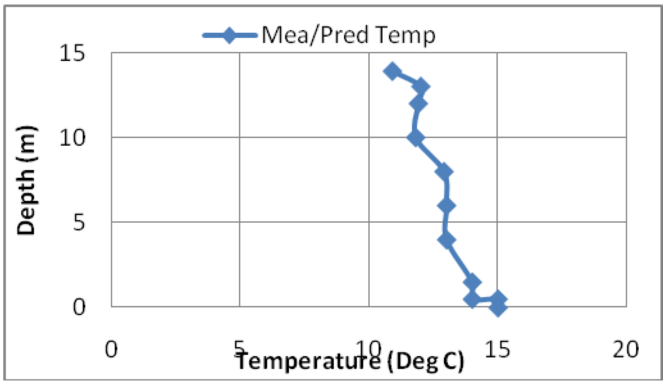


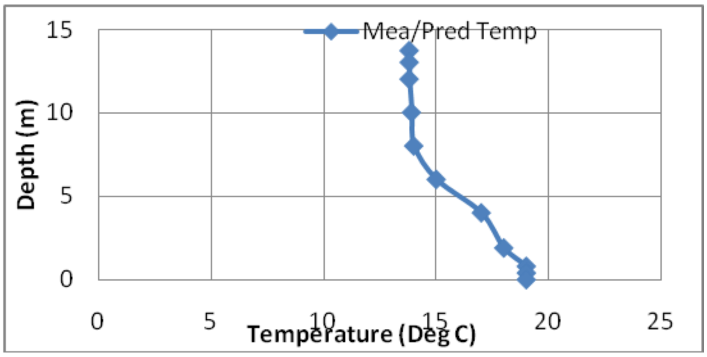
Fig.3: Measured and Predicted Temperature Variation with Depth Using Agunwamba (1997) Experimental Work at Nsukka WSP



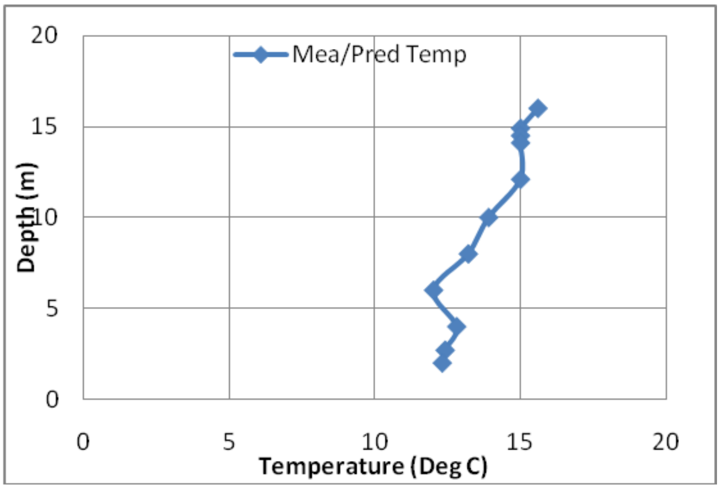


Feb. 13, 1980 April 23, 1980





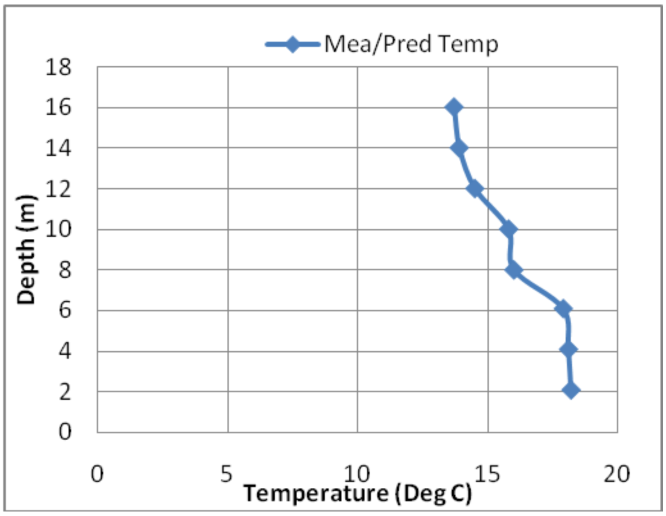
March 12, 1980 May 15, 1980

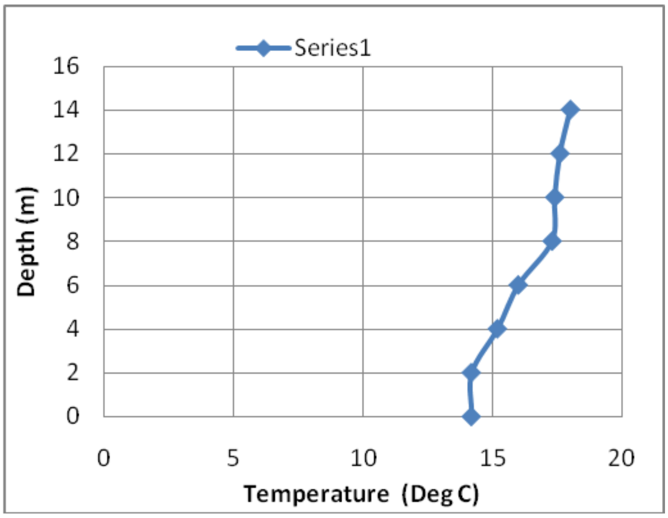


April 19, 1980

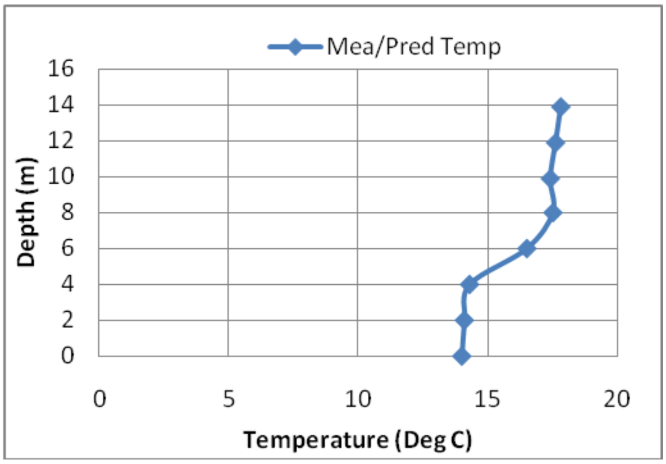
Fig.4: Measure and Predicted Temperature Variation with Depths Using Moreno- Grau & others (1984) Experimental Data for February 13,

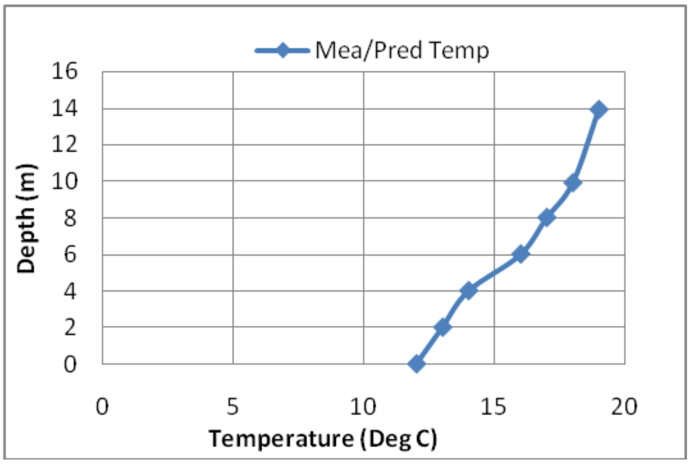
March12, April23, and May 15, (1980)





March 26, 1980 May 7, 1981





April 7, 1981 May 21, 1981

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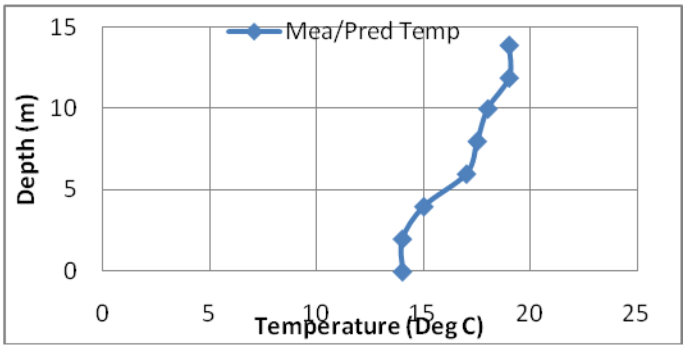
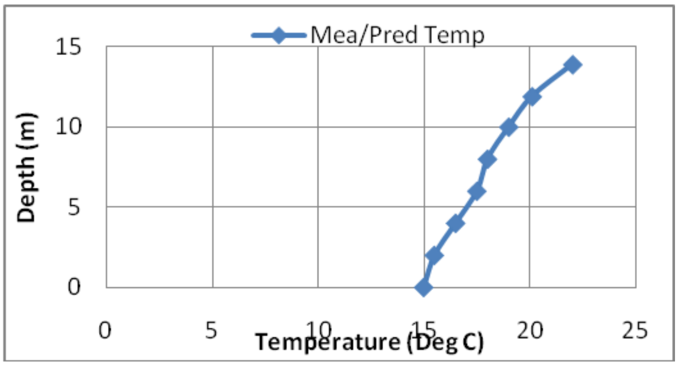




April 23, 1981 May 28, 1981

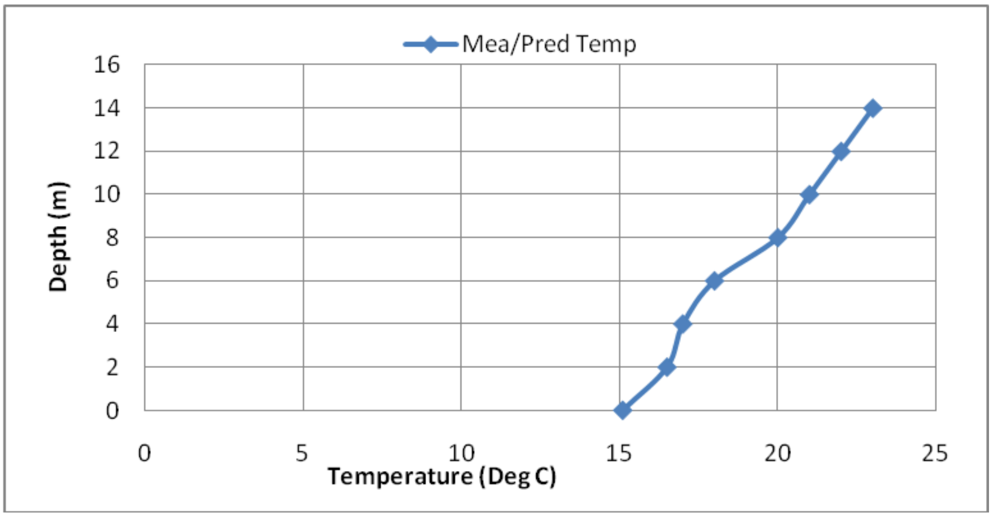
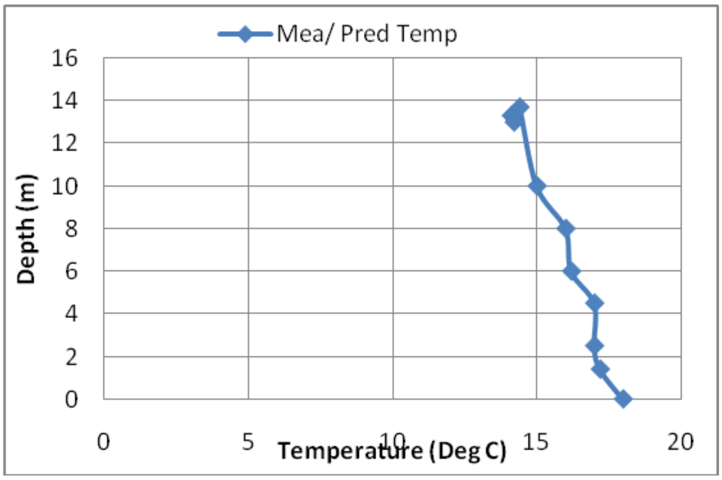
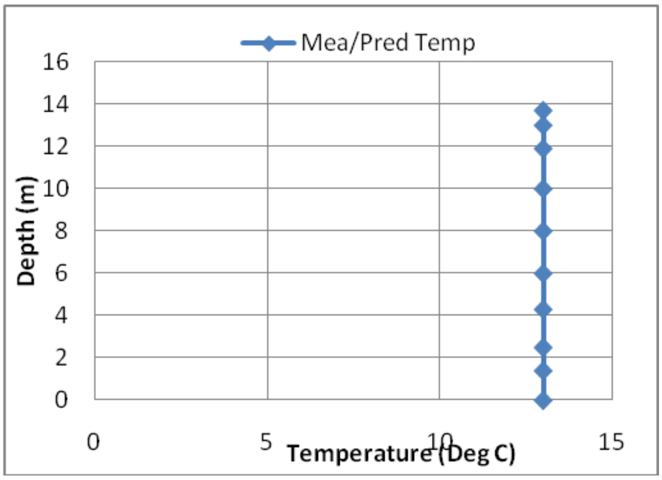
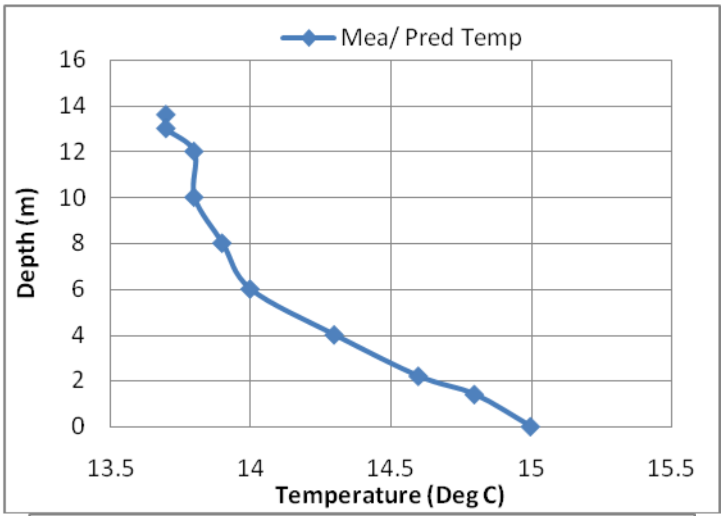


Fig.5: Measure and Predicted Temperature Variation with Depths Using Moreno- Grau & 0thers (1984) Experimental Data for June, 1981.







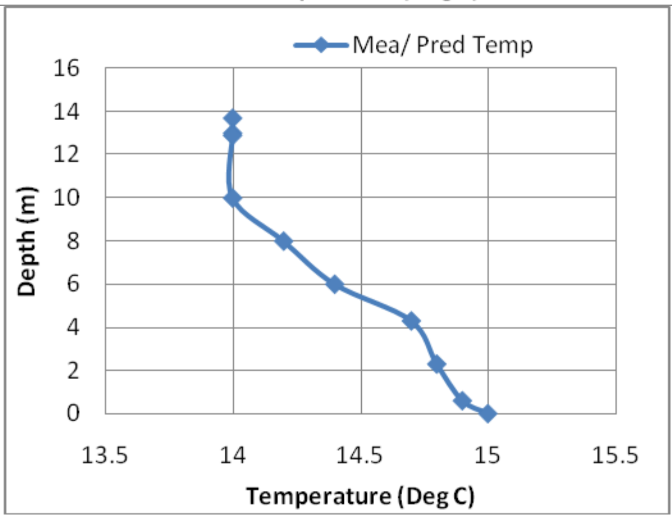


Fig.6: Measure and Predicted Temperature Variation with Depths Using Moreno-Grau & others (1984) Experimental Data.

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