A NUMERICAL STUDY OF THE THERMAL EFFECTS ON LOCAL WATER BODIES DUE TO CHANGES IN THE ENVIRONMENT

By,

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ABSTRACT OF THE THESIS

A numerical study of the thermal effects on local water bodies due to changes in the environment

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The study of global warming and its effects is becoming increasingly popular due to steady increase in the environmental pollution. Local warming of a particular place which in turn contributes to the global warming can be studied through temperature variations of the local water bodies due to changes in the environment. In the present work, using the weather data obtained for New Brunswick, a general trend for variation in ambient temperature during the year is determined by fitting suitable curves using curve-fitting technique. Using this, the transient temperature distribution in the lake is determined numerically. The effect of many driving parameters such as ambient temperature, relative humidity, wind speed, solar flux, equilibrium temperature, diffusivity and surface heat loss on the temperatures of the lake are studied in detail using a one-dimensional transient model. The governing equations are solved numerically using finite differences method. The results of this work show the transient temperature distribution in the lake over the year and the variation in temperatures due to external changes in the environment.

ACKNOWLEDGEMENTS

I wish to acknowledge my heartfelt gratitude to Dr. Yogesh Jaluria for having suggested this problem and for the continued inspiration and support provided through the research work. I am very thankful to Dr. Jaluria for agreeing to be my advisor and mentoring me through this great learning experience in the form of this research problem. This thesis wouldn't have been possible without his constant guidance.

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-NIKHIL BHARADWAJ

CONTENTS

NOMENCLATURE

B	Atmospheric Radiation Factor
C_p	Specific Heat of fluid (J/kgK)
h	Convective Heat Transfer Coefficient (W/m^2K)
i	Vertical Node Position
k	Thermal Conductivity of the fluid (W/mK)
P	Atmospheric Pressure (kPa)
p_a	Partial vapor pressure in the ambient medium (kPa)
p_s	Partial vapor pressure at surface (kPa)
Q	Total Heat Loss (W/m^2)
Qa	Long Wave Radiation absorbed by the body of water (W/m^2)
Qbr	Heat Flux due to back radiation (W/m^2)
Qc	Heat Flux due to convection (W/m^2)
Qe	Heat Flux due to evaporation (W/m^2)
Qs	Heat Flux due to solar heating (W/m^2)
Qw	Long Wave Radiation leaving the body of water (W/m^2)
RH	Relative Humidity
t	Time (days of the year)
z	Depth of the lake (m)

T	Local Temperature (K)
T_a	Ambient Temperature (K)
T_b	Bottom Temperature (K)
T_e	Equilibrium Temperature (K)
T_s	Surface Temperature of lake (K)
V_e	Wind Speed (m/s)

Greek Symbols

α	Thermal Diffusivity (m^2/s)
ρ	Fluid Density (kg/m^3)
σ	Stefan-Boltzmann Constant (W/m^2K^4)

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF WARMING

Global Warming is the increase of Earth's average surface temperature due to the effect of carbon dioxide (greenhouse gas) emissions from burning fossil fuels or from deforestation, which trap heat that would otherwise escape from the Earth. This is a type of *greenhouse effect*.

Earth's temperature depends on the balance between energy entering and leaving the planet's system. When incoming energy from the sun is absorbed by the Earth system, Earth warms. When the sun's energy is reflected back into space, Earth avoids warming. When absorbed energy is released back into space, Earth cools. Many factors, both natural and human, can cause changes in Earth's energy balance, including:

- Variations in the sun's energy reaching Earth.
- Changes in the reflectivity of Earth's atmosphere and surface.
- Changes in the greenhouse effect, which affects the amount of heat retained by Earth's atmosphere.

Records show that the climate system varies naturally over a wide range of time scales. In general, climate changes prior to the Industrial Revolution in the 1700s was explained by natural causes such as changes in solar energy, volcanic eruptions, and natural changes in greenhouse gas (GHG) concentrations. However, recent climate changes cannot be explained by natural causes alone. Research indicates that natural causes do not explain most observed warming, especially warming since the mid-20th century. Rather, it is extremely likely that human activities have been the dominant cause of that warming. This has triggered a lot of research groups to study warming in detail to get an idea about its impacts on mother earth so that appropriate measures can be taken as early as possible to save the earth for future generations.

Some of the major impacts of Global Warming are as follows:

- Rising Seas - inundation of fresh water marshlands, low-lying cities, and islands with seawater.
- Changes in rainfall patterns - droughts and fires in some areas, flooding in other areas.
- Increased likelihood of extreme events - such as flooding, hurricanes, etc.
- Melting of the ice caps - loss of habitat near the poles. Polar bears are now thought to be greatly endangered by the shortening of their feeding season due to diminishing ice packs.
- Melting glaciers - significant melting of old glaciers is already observed.
- Widespread vanishing of animal populations - following widespread habitat loss.
- Spread of diseases - migration of diseases such as malaria to new, now warmer, regions.
- Bleaching of Coral Reefs due to warming seas and acidification due to carbonic acid formation - *One third* of coral reefs now appear to have been severely damaged by warming seas.

Global warming is indirectly the sum total of local warming of individual cities, towns and villages across the world. The best way to calculate the global warming is by studying local warming of individual places over a certain period of time. In order to study local warming all the factors contributing to the warming of that particular place have to be carefully considered. One of the easier method to study local warming is by studying the behavior of water bodies like lakes, ponds or rivers in close proximity to the place under study.

1.2 Review of Previous Work

The primary reason for considering this topic is due to the ease of studying warming through the behavior of native water bodies. Raphael (1962) developed a procedure for predicting the temperature of various water bodies such as shallow lakes, flowing streams and detention reservoirs, from weather records, inflow and outflow characteristics, the surface area and the volume of the water body [1]. Delay and Seaders (1966) developed a mathematical model for predicting temperature in rivers and reservoirs. They computed the net monthly energy exchange from the reservoir and then distributed it vertically so that the resulting temperature gradients approximated the standard for each month [2]. Dake and Harleman (1969) developed a theoretical model for the time dependent vertical temperature distribution in a deep lake, during the yearly cycle. They took a heat-flux balance at the water surface, which accounts for back radiation and evaporative loss as a boundary condition [3]. Based upon the assumption of horizontal isotherms, at all times, Huber, Harleman and Ryan (1972) developed a mathematical model, for determining the vertical temperature distribution in stratified reservoirs, which include the effects of heat sources and sinks at the boundaries, internal absorption of solar radiation and heat transport by convection and diffusion [4]. Snider and Viskanta (1975) carried out an analysis for the time dependent thermal stratification in the surface layers of stagnant water due to solar radiation. They used finite difference methods to obtain the transient temperature distribution, by solving the one-dimensional energy equation, for combined conduction and radiation energy transfer mechanisms [5]. Dr. Jaluria, Variyar and Mehta (1976) developed a mathematical model to predict the temperature and velocity profiles in a body of water, due to the basic mechanisms in the presence of winds, cloudiness, back radiation etc. They computed the equilibrium average surface temperature, which is defined as the temperature attained by the surface, if the ambient conditions are held constant at specific values, and studied the heat transfer mechanism at the surface in detail. They studied certain specific, simplified, one and two-dimensional models in detail. The work concentrated largely on steady state models [6]. Cha and Dr. Jaluria conducted an analytical and numerical investigation on heat rejection to the surface layer and on energy extraction from the storage zone of a salt gradient solar pond [7].

1.3 Present Work

In the present work, a one-dimensional mathematical model in the form of finite difference equations has been developed to determine the vertical temperature distribution in the lake. Using the weather data of New Brunswick, the ambient temperature variation for 365 days in a year was studied in detail and a suitable curve fitting technique was employed to get curves for ambient temperature variation.

Using the ambient temperature variation, the net surface heat exchange was computed by using a method similar to that outlined by Dr. Jaluria, Variyar and Mehta [6] taking into consideration changes in solar flux, wind speed, relative humidity etc. The surface temperature is determined, which is employed in the computation of the vertical temperature distribution. The effects of various governing parameters such as ambient temperature, back radiation and diffusivity are studied in detail.

CHAPTER 2

NUMERICAL MODEL AND METHOD OF SOLUTION

The behavior of the water body is largely determined by the extent to which it interacts with the surrounding environment. Hence in developing the model, the mathematical representation of the various mechanisms underlying its interaction with the environment is of considerable importance. The basic assumptions of the lake while developing the model are as follows:

- The lake/ water body is finite.
- No energy transfers across the sides and bottom i.e. energy transfer occurs only at the surface.
- The sides of the lake are absolutely vertical and the bottom is absolutely horizontal and flat.
- Temperature variation in the lake is only in the vertical direction, the horizontal gradients being neglected.
- Ambient conditions are functions of time.
- For all calculation purposes, following is the break of seasons:
    - Summer – June, July & August
    - Fall – September, October & November
    - Winter – December, January & February
    - Spring – March, April & May

2.1 ENERGY EXCHANGE AT THE SURFACE

Considerable information exists on the underlying physical process concerning energy transfer at the surface of the water body. As shown in Figure 2.1 the dominant modes are evaporation, convection, back radiation and solar heating. For steady-state conditions, the energy gained by the lake due to solar heating is lost by evaporation, convection and back radiation. Therefore,

$$Q = Qe + Qc + Qbr - Qs \tag{2.1}$$

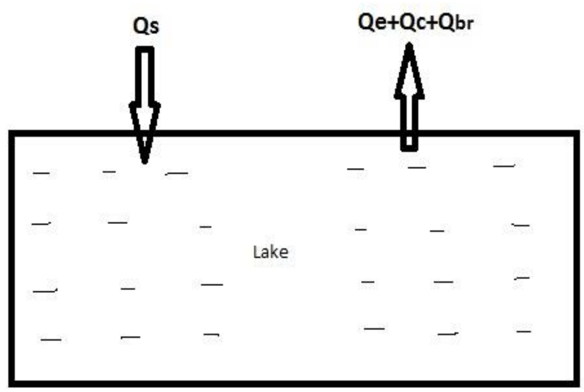

Figure 2.1 – Dominant modes of Surface Heat Exchange

2.1.1 Evaporation:

When the vapor pressure of ambient air is less than the saturated vapor pressure at the water surface temperature, water evaporates into the air removing heat mainly due to the energy required to evaporate the water and to a small extent by the secondary heat transfer due to the sensible heat contained in the water removed by evaporation. The correlation used to calculate the heat transfer by evaporation is obtained from the work of Raphael [1].

$$Qe = 21.7 * Ve * (p_s - p_a) \tag{2.2}$$

Where $$p_a = p_s * RH \tag{2.3}$$

2.1.2 Convection:

Whenever a temperature difference exists between the ambient air and the water surface, sensible heat is convected to or from the body of water. The basic equation for the convective heat transfer from the water surface to the air is given by

$$Qc = h * (Ts - Ta) \tag{2.4}$$

where h is the surface heat transfer coefficient. The value of h is largely dependent on the condition of the air in contact with the water and hence is a function of wind speed, it's temperature, direction and turbulence level etc. The correlation used to calculate the heat transfer by convection for North American conditions is obtained from the work of Raphael [1].

$$Qc = 0.0041 * Ve * P * (Ts - Ta) \tag{2.5}$$

2.1.3 Back Radiation:

Effective back radiation may be defined as the difference between Qw, the longwave radiation leaving a body of water and Qa, the longwave radiation from the atmosphere being absorbed by the body of water. Atmospheric radiation does not follow a simple law as it is a function of many variables such as the air moisture content, temperature, thickness of ozone layer, CO_2 concentration, cloud cover etc. However, since most weather observations give cloud amount in tenths of sky obscured, the variation of the atmospheric radiation factor B, has been given as a function of cloud cover, air temperature and vapor pressure by Raphael. The correlation used to calculate the heat transfer by back radiation is obtained from the work of Raphael [1].

$$Qbr = Qw - Qa = 0.97 * \sigma * (Ts^4 - B*Ta^4) \quad (2.6)$$

2.1.4 Solar Heating:

At a point outside the atmosphere of the earth, radiant energy is received from the sun on a surface normal to its rays at a rate of 1165 K.cal/hr/sq.m. This value called the solar constant fluctuates slightly during the course of the year because of sunspots and variation in the distance between the sun and the place on the earth in consideration for the purpose of study. Studies show the solar heating varies for New Brunswick from anywhere between a low of 40 W/m^2 in the winter to 240 W/m^2 in the summer. A curve fitting technique was developed using MATLAB to calculate the variation of the solar heating during different times of the year. The correlation used to calculate the heat transfer by solar heating is obtained as:

$$Qs = 251.4 * \sin(0.007041*(t-1) + 0.402) \quad (2.7)$$

Where, t is the time in days starting from January 1.

Substituting equations (2.2), (2.5), (2.6) & (2.7) in equation (2.1) the equilibrium temperature Te at which the total energy transfer at the surface is zero can be calculated. A frequently employed expression for surface energy exchange is:

$$Q = h\,(Ts - Te) \quad (2.8)$$

where the heat transfer coefficient h may be determined from the gradient of Q v/s Ts plot at equilibrium temperature Te. Therefore, both h and Te can be computed at various times during the year since they are dependent on ambient conditions. It may be determined for a given lake by a detailed study of Q and Te in terms of various mechanisms outlined above. Clearly this approach is a quasi-steady one. However, it has been found to be quite satisfactory for the study of natural water bodies.

2.2 GEOMETRY AND THE COORDINATE SYSTEM

The geometry and the coordinate system for the one-dimensional temperature distribution in the lake of rectangular cross-section in the vertical plane is shown in Figure 2.2. The origin for the Cartesian coordinate system shown is located at the upper left corner of the rectangle. The direction towards the right from the origin, as indicated in the figure, is taken as positive for the horizontal time coordinate t, and the downward direction which coincides with the gravity direction is taken as positive for the vertical depth coordinate z. Heat loss at the top surface of this configuration is indicated by Q.

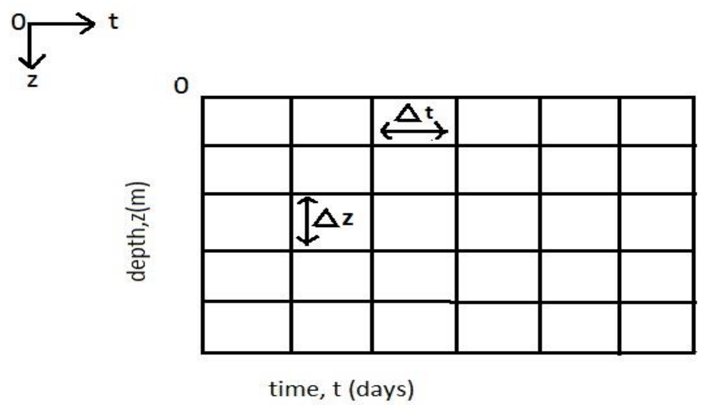

Figure 2.2 - Coordinate system for the one-dimensional temperature distribution in the lake

2.3 ONE DIMENSIONAL MODEL

A one dimensional model physically represents a condition when the lateral mixing in the lake is so vigorous that only vertical exchange of heat needs to be considered. It has been found by Raphael [1] that the eddy diffusivity in the vertical direction for stratified water bodies is around one-hundredth the value in the horizontal direction. Therefore, horizontal mixing is much more vigorous, mainly due to buoyancy forces resulting from the temperature dependent density differences.

For a one dimensional model, since temperature variation exists only in the vertical direction, the boundary conditions have to be specified at the surface and at the bottom. Energy exchange to the environment occurs at the top surface. An adiabatic thermal condition is assumed at the side walls of the lake and thus no energy transfer occurs on the sides. Thus the governing one dimensional energy equation for the lake becomes:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \quad (2.9)$$

With the conditions:

$$T = Ts \text{ at } i = 0 \quad (2.10)$$

$$T = Tb \text{ at } i = z \quad (2.11)$$

$$\alpha \frac{\partial T}{\partial z} - \frac{Q}{\rho C_p} = 0 \text{ at } i = 0 \quad (2.12)$$

An analytical solution of the above parabolic equation may be obtained by employing methods such as separation of variables and Laplace transforms. But for complex boundary conditions and arbitrary initial temperature distributions, such analytical solutions become very involved and numerical methods are much more convenient. So the numerical scheme has been chosen to solve the present problem.

2.4 Finite Difference Scheme

Transient conduction problems are very frequently encountered in the study of natural phenomena. Examples include study of daily, seasonal and yearly variation of temperature in water bodies, earth's surface etc. to determine environmental impacts, warming etc. In such problems, interest lies mainly in the study of variation in temperature with time and in the temperature distribution within the body for various time intervals.

Transient conduction refers to the set of problems in which the temperature in the conduction region varies with time. In such problems, usually the body undergoes an initial change over a period of time and eventually reaches a steady-state. The temperature may then continue to vary periodically with time for the rest of the duration. For such periodically varying processes best results can be obtained by studying the temperature distribution over a complete cycle of operation.

In our problem, we consider the simple case of one-dimensional transient conduction without heat generation and with constant material properties. The governing equation in the Cartesian coordinate system is given by Equation 2.9. The solution to this parabolic equation is obtained for increasing time using two boundary conditions and an initial condition which is the temperature distribution at time, t=0. Using the initial temperature distribution, the temperatures are obtained at the next time step. The results thus obtained are then used to evaluate the temperatures till the end of the second time step. Thus the solution proceeds for increasing time until results are obtained over a specified time or until the steady-state is attained [8].

The lake of depth z is divided into i equal elements each of length Δz and t is the time at which the temperature is to be calculated. The governing differential equation 2.9 can be written in the finite difference form as follows:

$$\frac{T_i^{t+1} - T_i^t}{\Delta t} = \alpha \frac{T_{i+1}^t - 2T_i^t + T_{i-1}^t}{\Delta z^2} \quad (2.13)$$

Separate finite difference equation is written for the surface, intermediate and bottom elements as follows,

For surface,

$$\frac{T_i^{t+1} - T_i^t}{\Delta z} = - \frac{Q}{\alpha \rho C_p} \quad (2.14)$$

For intermediate elements,

$$\frac{T_i^{t+1} - T_i^t}{\Delta t} = \alpha \frac{(T_{i+1}^t - 2T_i^t + T_{i-1}^t)}{\Delta z^2} \quad (2.15)$$

For bottom element,

$$\frac{T_i^{t+1} - T_i^t}{\Delta t} = \alpha \frac{(-T_i^t + T_{i-1}^t)}{\Delta z^2} \qquad (2.16)$$

The analysis of this transient solution begins on January 1st, when the lake is in the fully mixed condition and is carried out over the entire year taking each time step as 1 day. This gives the temperature distribution in the lake for different depths for the entire year. The iteration is continued till the temperature distribution in the lake reaches steady state i.e. unchanged from one year to the following year.

Previous studies have shown that the choice of initial condition / temperature distribution on January 1st was found to affect the convergence significantly. The closer the initial guess is to the final solution, the faster will be the convergence as expected [9]. So based on this, the initial guess was taken based on

$$T^0(i) = Te, \text{ for all } i \qquad (2.17)$$

CHAPTER 3

RESULTS AND DISCUSSION

3.1 AMBIENT TEMPERATURE VARIATION

The pattern of the weather data obtained over several years for New Brunswick was studied carefully. Using this pattern an average ambient temperature during different times of the year was picked as follows:

Time of the year	Temperature (C)
January 1st	5
January 15th	3.5
February 15th	7.5
March 15th	12.5
April 15th	17.5
May 15th	22.5
June 15th	27
July 15th	30
August 15th	27
September 15th	22.5
October 15th	17.5
November 15th	12.5
December 15th	7.5
December 31st	5

Table 3.1

The curve-fitting tool in MATLAB was used to plot a sine curve for the periodic variation of ambient temperature over the year. A standard equation for the variation of the ambient temperature with time was determined. See Appendix 1 for the equations & coefficients. The curve fit method used was fairly accurate since the R^2 value obtained was 0.9997 with 95% confidence as the goodness of fit. To check the validity, the same technique was used varying the starting temperature on Jan 1st by ±5 (^{0}C). Figure 3.1 shows the variation of Ambient temperature with time with starting temperature on Jan 1st at 5^{0}C. Figure 3.2 shows the variation of Ambient temperature with time with starting temperature on Jan 1st at 10^{0}C. Figure 3.3 shows the variation of Ambient temperature with time with starting temperature on Jan 1st at 0^{0}C.

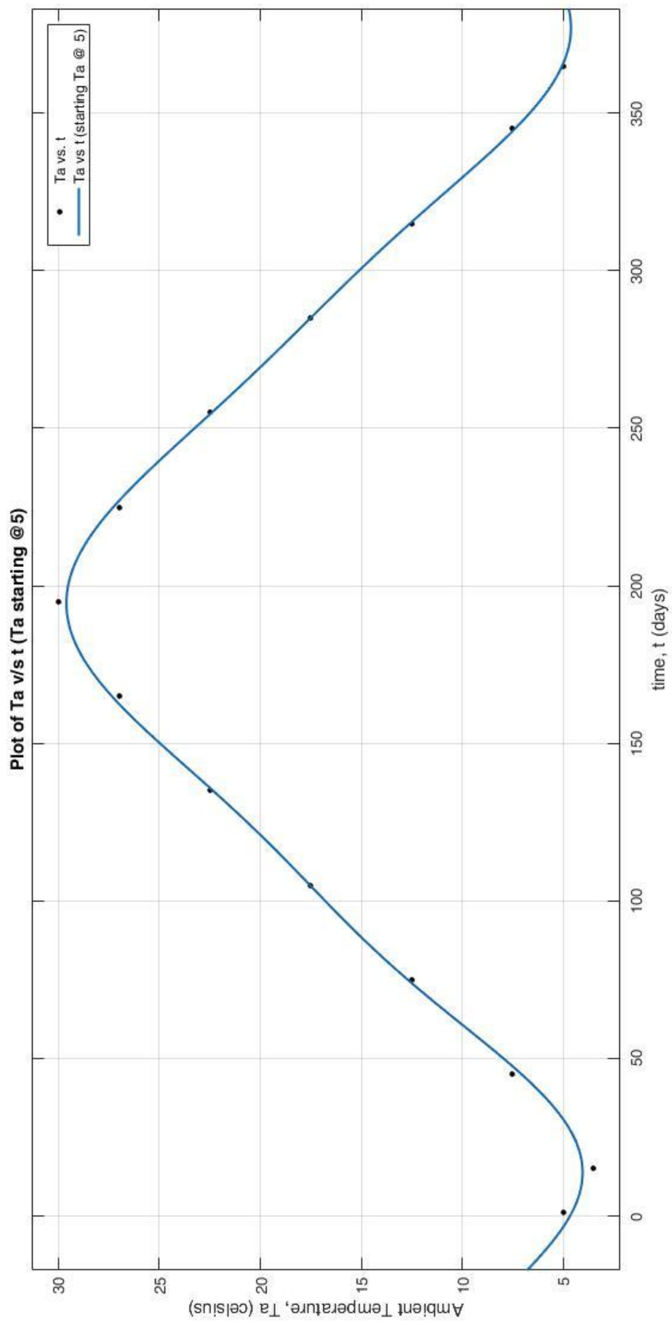

Figure 3.1 - Plot of Ambient Temperature v/s time starting Jan 1st @ 5^0C

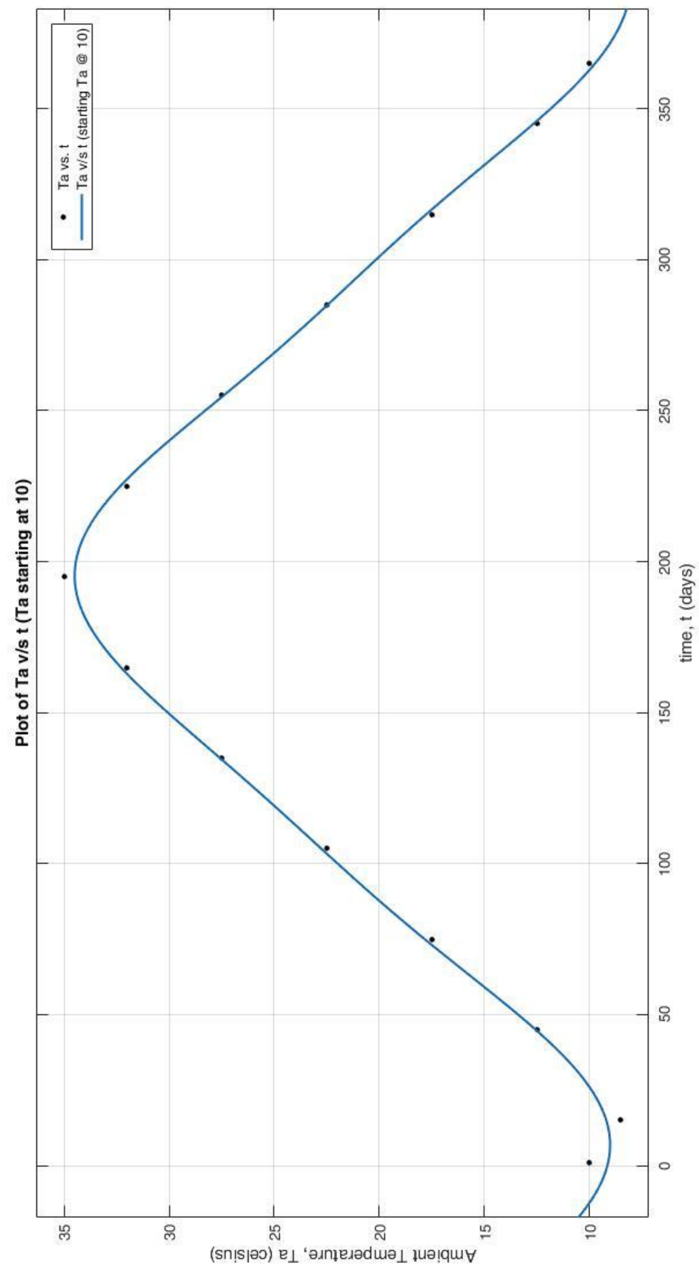

Figure 3.2 - Plot of Ambient Temperature v/s time starting Jan 1st @ 10^0C

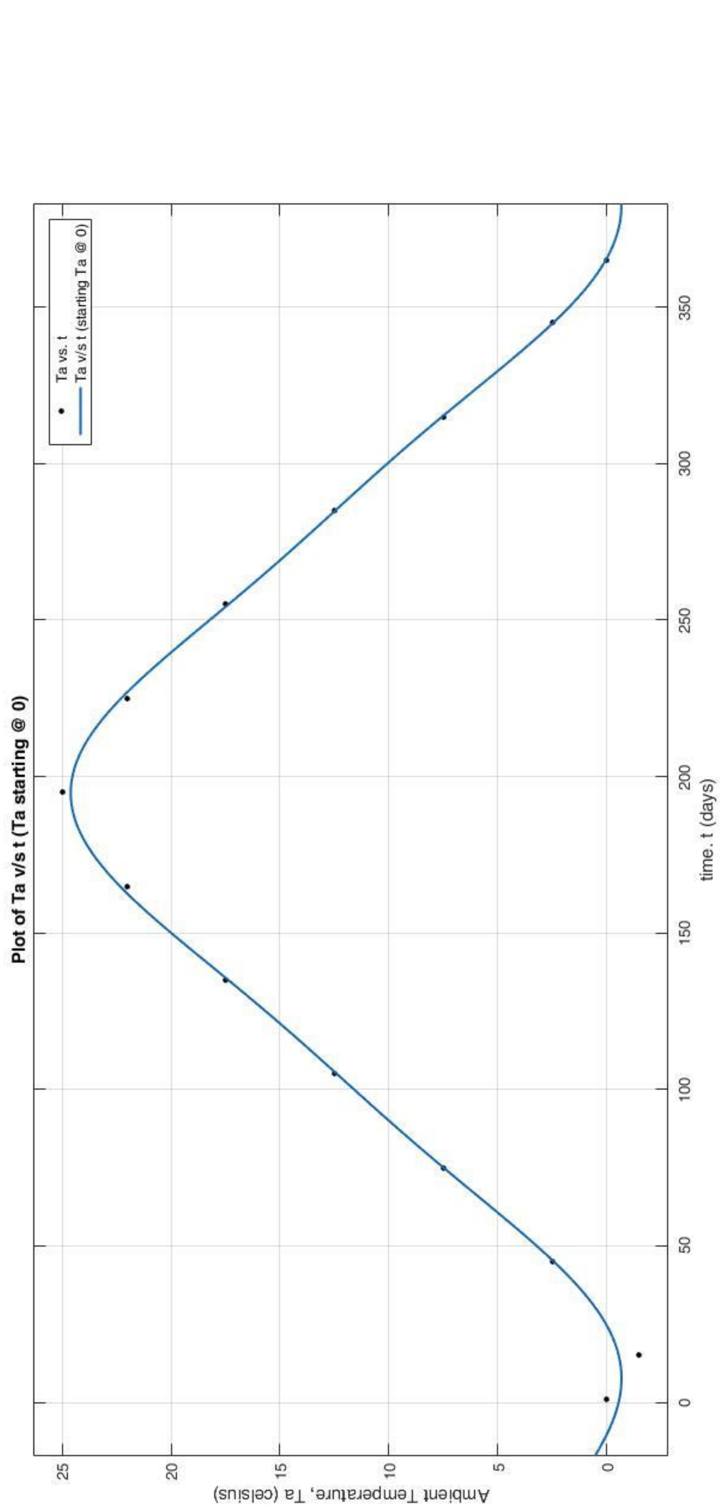

Figure 3.3 - Plot of Ambient Temperature v/s time starting Jan 1st @ 0^0C

3.2 Surface Heat Exchange

The study of the above ambient temperatures reveals the average winter temperature for the winter months of December, January and February to be 5^0C, the average spring temperature for the spring months of March, April and May to be 17.5^0C, the average summer temperature for the summer months of June, July and August to be 30^0C and the average fall temperature for the fall months of August, September and October to be 17.5^0C. So these standard averages for each season was used for calculating the variation of the Total Heat Loss at the water surface with respect to the water surface temperature.

Firstly, the variation of Total Heat Loss at the surface with water surface temperature was studied for various wind speeds for all seasons. Figure 3.4 shows this variation at average winter ambient temperature of 5^0C, Figure 3.5 shows the variation at average spring and fall ambient temperature of 17.5^0C and Figure 3.6 shows the variation at average summer ambient temperature of 30^0C.

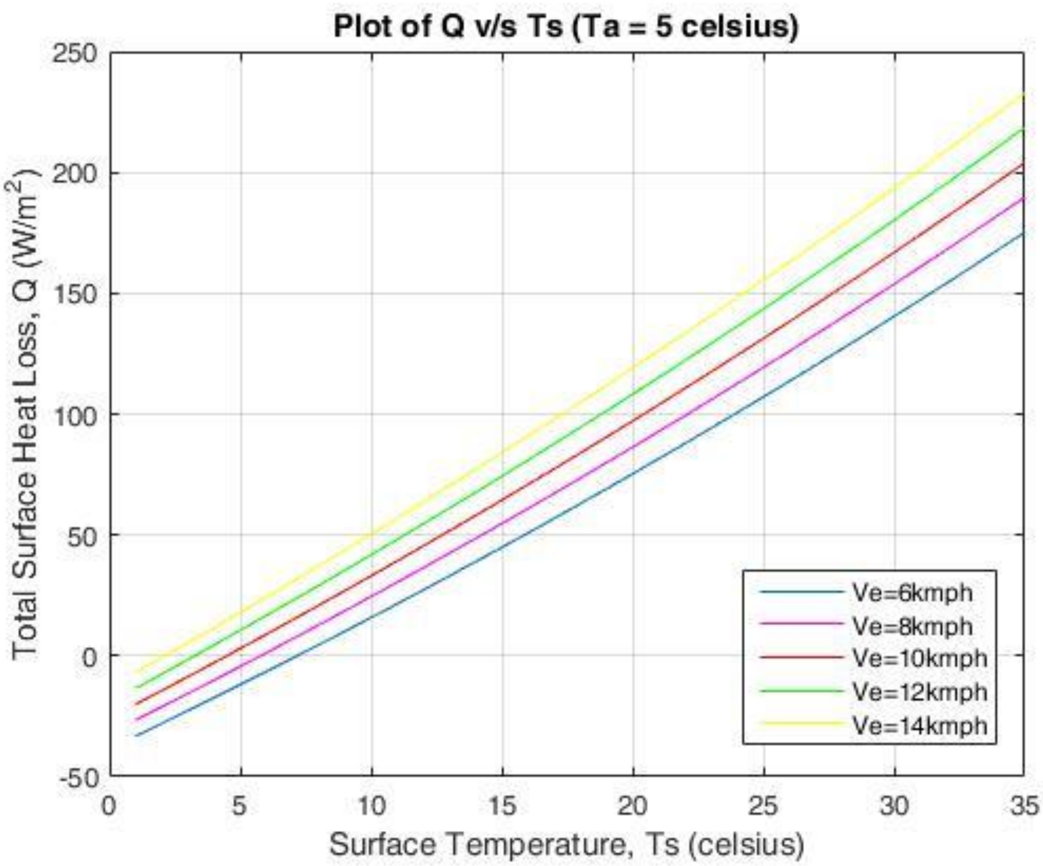

Figure 3.4 - Plot of Total Surface Heat Loss v/s Water Surface Temperature for winter

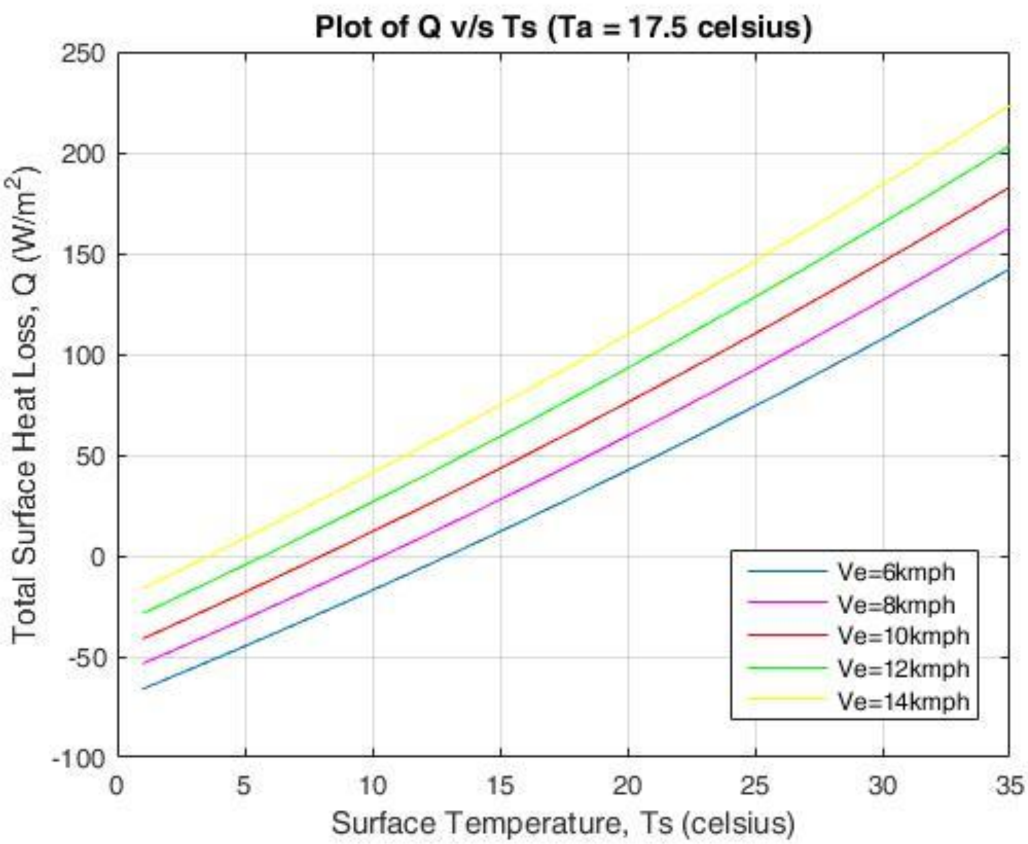

Figure 3.5 - Plot of Total Surface Heat Loss v/s Water Surface Temperature for spring and fall

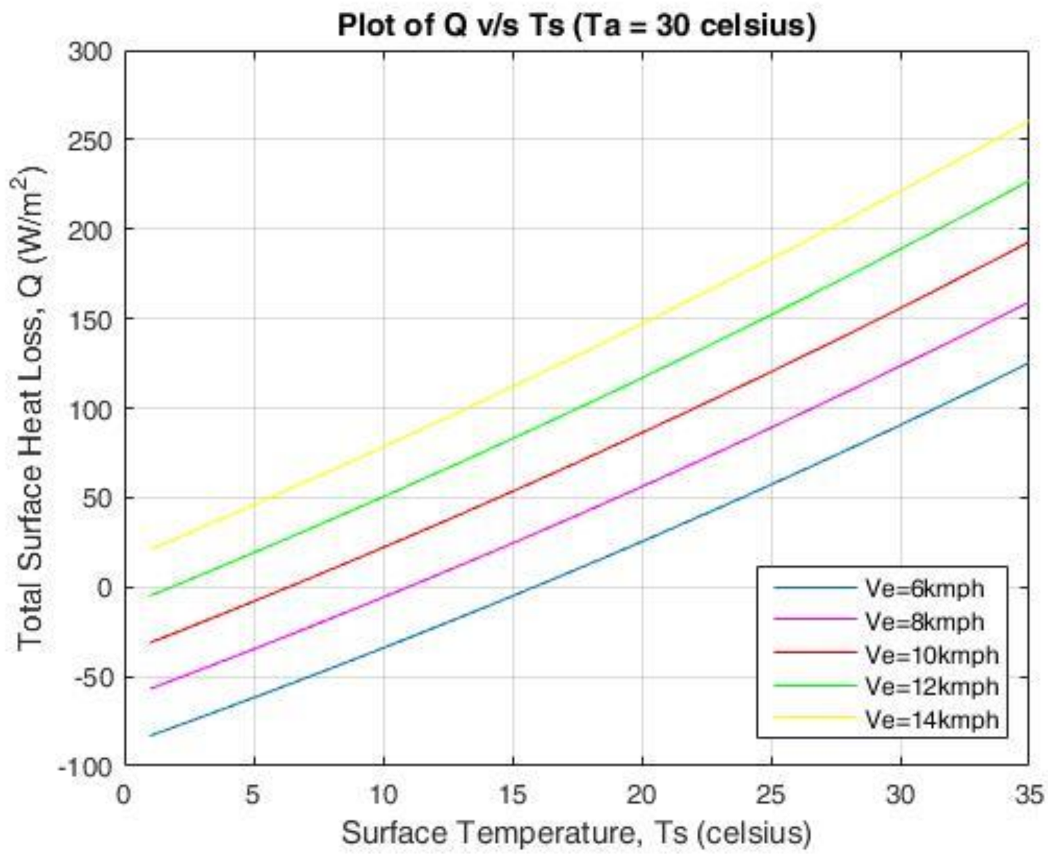

Figure 3.6 - Plot of Total Surface Heat Loss v/s Water Surface Temperature for summer

So, in the above figures 3.4, 3.5 & 3.6 we observe the variation of energy lost by the water surface as a function of surface temperature and wind speed. This variation was computed keeping in mind the various factors contributing to the total heat loss like evaporation, solar heating, back radiation and convection. The results show that at lower surface temperatures, the change in wind speed does not have much effect on the surface heat exchange for winter but the variation becomes more and more considerable as we to move to the spring/ fall and summer season. However, at higher surface temperatures, even a small change in wind speed does play a significant role in the change in surface heat transfer irrespective of the season. For all seasons, heat loss at the surface increases with increase in surface temperature. The total surface heat loss increases with increase in wind speed due to greater convection loss and greater evaporation.

In the above figures 3.4, 3.5 & 3.6, the intercept of the curves on the x-axis gives the values of equilibrium temperature, Te. So, the equilibrium temperature can be defined as the value of surface temperature at which the total surface heat loss is zero. It is observed that the equilibrium temperature increases with an increase in the ambient temperature keeping all other parameters as constant since it reduces the evaporation, thus requiring an increased surface temperature for energy balance. This variation is shown in Figure 3.7 for Ve = 6 km/hr. Also, the equilibrium temperature decreases with an increase in the wind speed keeping all other parameters as constant. This variation is show in Figure 3.8 for Ta = 5^0C.

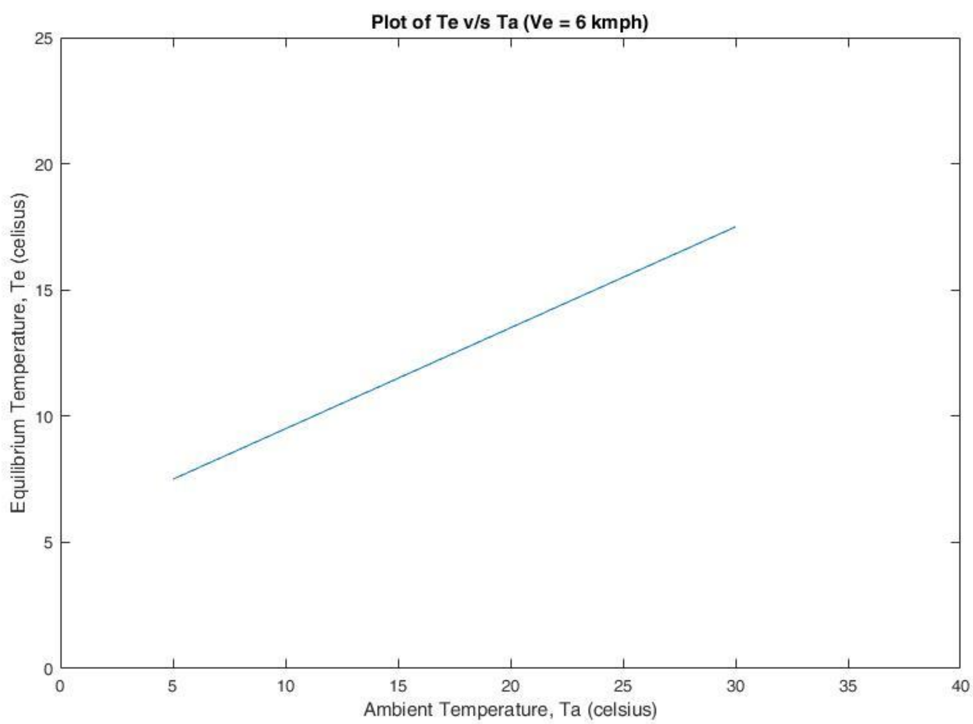

Figure 3.7 – Plot of Equilibrium Temperature v/s Ambient Temperature (Ve = 6 kmph)

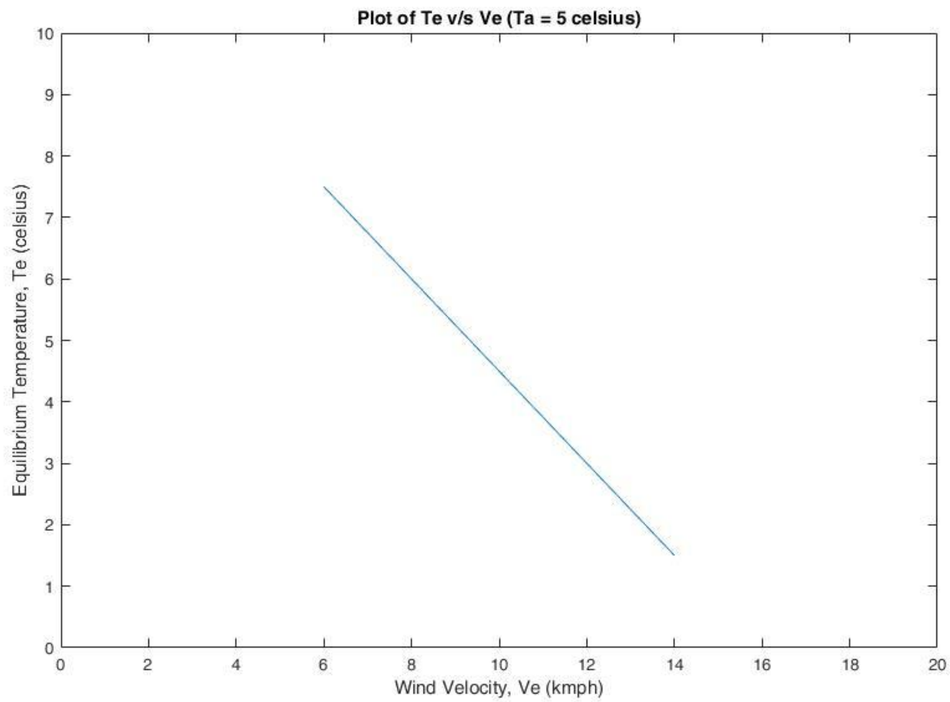

Figure 3.8 – Plot of Equilibrium Temperature v/s Wind Speed (Ta = 5^0C)

The slope of the curves in the plot of total surface heat loss v/s surface temperature at the equilibrium temperature gives the surface heat transfer coefficient for various seasons. It varies significantly with wind speed compared to other factors. So the variation with wind speed was studied for various seasons and it was observed that the surface heat transfer coefficient increases with increase in the wind speed. The results were plotted in Figure 3.9 at Ta = 30^{0}C. The values obtained conform with earlier studies made by Moore and Jaluria on Cayuga lake in New York [11].

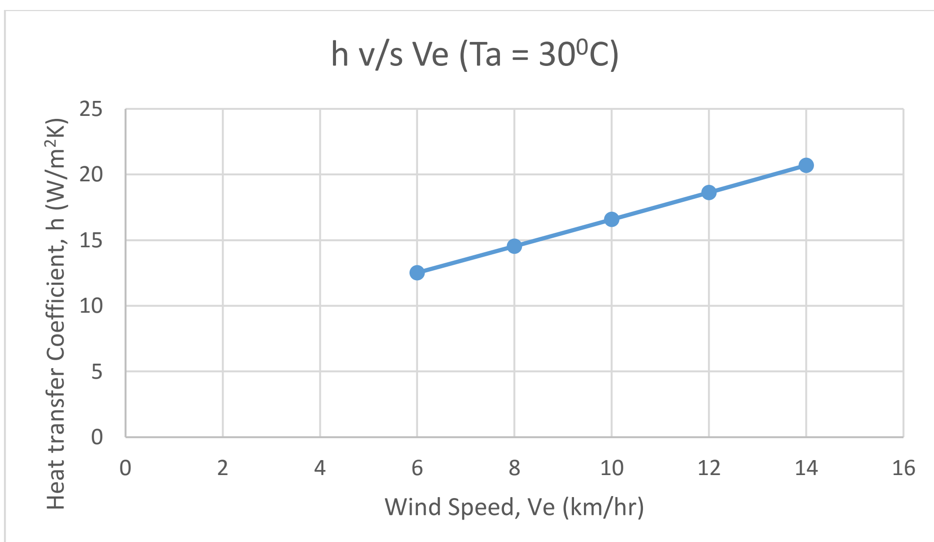

Figure 3.9 – Plot of Surface Heat Transfer Coefficient v/s Wind Speed (Ta = 30^{0}C)

3.3 Temperature Distribution

After studying the variation in ambient temperature over the year and surface heat exchange, the actual study of one-dimensional transient temperature distribution in the lake was carried out. Using the finite difference equations and the boundary conditions mentioned in Section 2.4, the surface temperature variation was calculated for three different depths of the lake. The studies were made for 2 different cases with Ambient Temperature starting at 5^0C on Jan 1st and Ambient Temperature starting at 0^0C and taking wind speed as 10 km/hr and atmospheric radiation factor as 0.8 and time step as one day. The initial guess for the surface temperature was made according to Equation 2.17 for the two cases. It was observed that after completion of one complete cycle i.e. one year, the surface temperature goes lower and lower as the depth of the lake decreases. The shallower the lake, larger will be the variation in surface temperature between Jan 1st and Dec 31st. Also, lower the ambient temperature lower will be the surface temperature as expected. The variations are shown in Figure 3.10 and Figure 3.11.

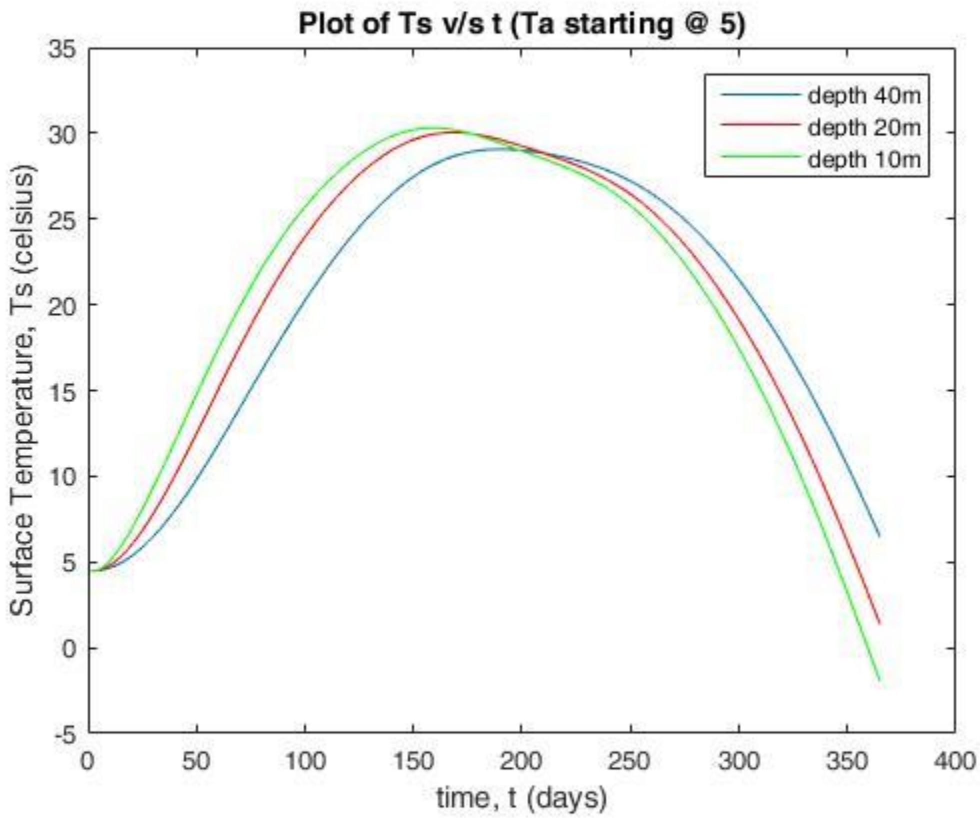

Figure 3.10 – Plot of Surface Temperature v/s time for Ta starting at 5^0C at various depths

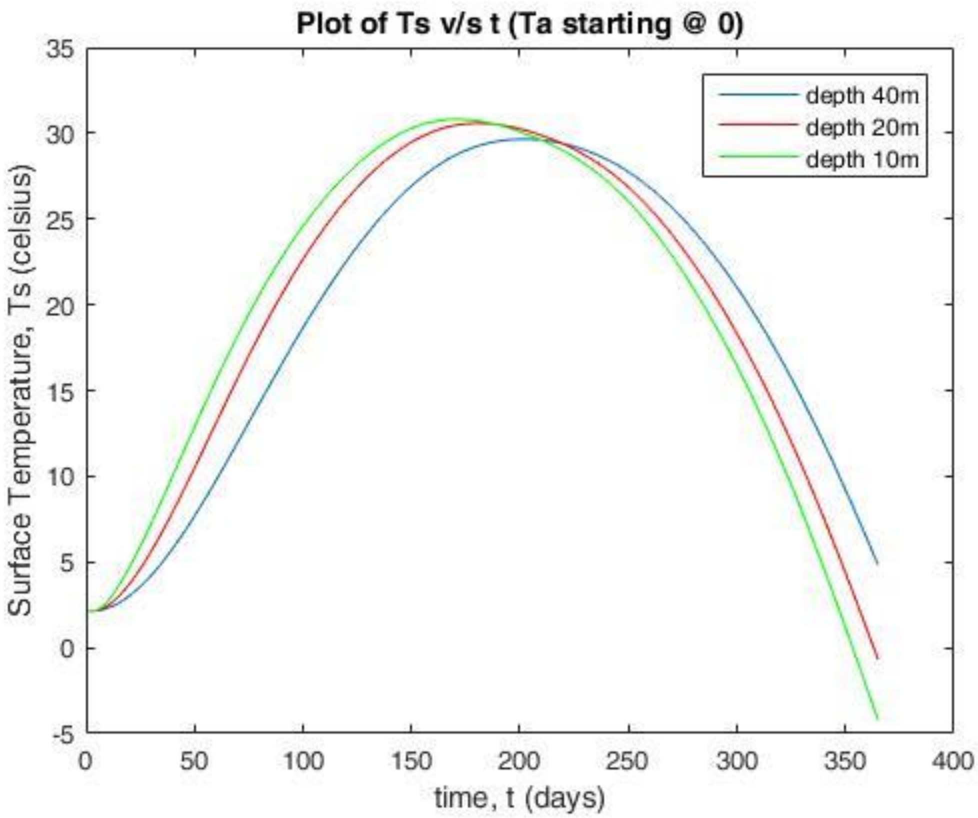

Figure 3.11 – Plot of Surface Temperature v/s time for Ta starting at 0^0C at various depths

Using these results the iterations were run for ambient temperature starting at $5^{0}C$ on Jan 1st for various depths until the variation in surface temperature from one year to another was close to zero. This variation shows that the surface of the lake achieves steady-state after 4 years of complete cycle and thereafter the variation in surface temperature from year to year is considerably nil. The results are plotted in Figure 3.12.

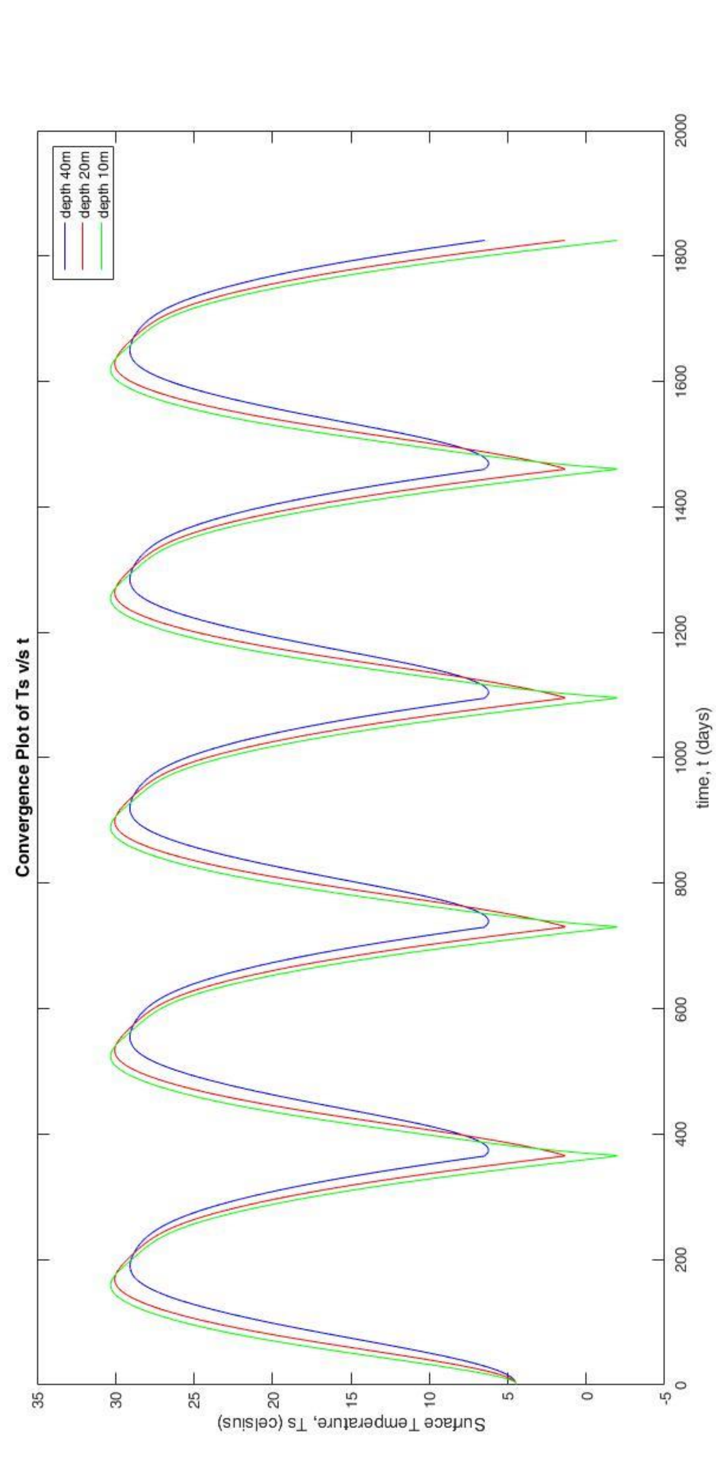

Figure 3.12 – Plot of Surface Temperature v/s time to show steady-state for various depths

The vertical temperature distribution in the lake at various times during the year was calculated using the finite difference equations and results obtained were plotted in Figure 3.13 and 3.14. Calculations were made starting ambient temperature at 5^0C with wind speed of 10 km/hr and atmospheric radiation factor as 0.8 and time period as 1 day. Figure 3.13 shows the vertical temperature distribution of the lake for the first cycle of study i.e. the first year and Figure 3.14 shows the vertical temperature distribution once the lake achieves steady-state. The temperature profile indicates that on Jan 1^{st} the lake is in a fully mixed condition. As winter progresses the ambient temperature starts to drop and reaches a minimum value on Jan 15^{th} and the lake starts to lose energy until the surface reaches the winter minimum temperature. After this the ambient temperature starts to increase, as a result the lake starts gaining heat through the surface which is slowly passed on to the lower layers. This begins the stratification in the layers of the lake. The surface temperature starts to increase rapidly since it starts receiving heat from the ambient air as the year progresses i.e. during spring and summer. However, the temperatures at the lower depths increase gradually, since it slowly receives heat from the heated upper layers. This continues till the surface temperature reaches a maximum somewhere around July 15^{th}. After this, the fall season begins and the ambient temperature starts to drop. The top surface layer of the lake starts to lose heat resulting in an isothermal top layer. The surface temperature reduces rapidly while the bottom layers slowly gain heat from the hotter upper layers. De-stratification starts to occur with the onset of winter and the lake becomes fully mixed again at the end of the year with temperatures close to that on Jan 1^{st} and the cycle repeats until the temperatures reach steady-state.

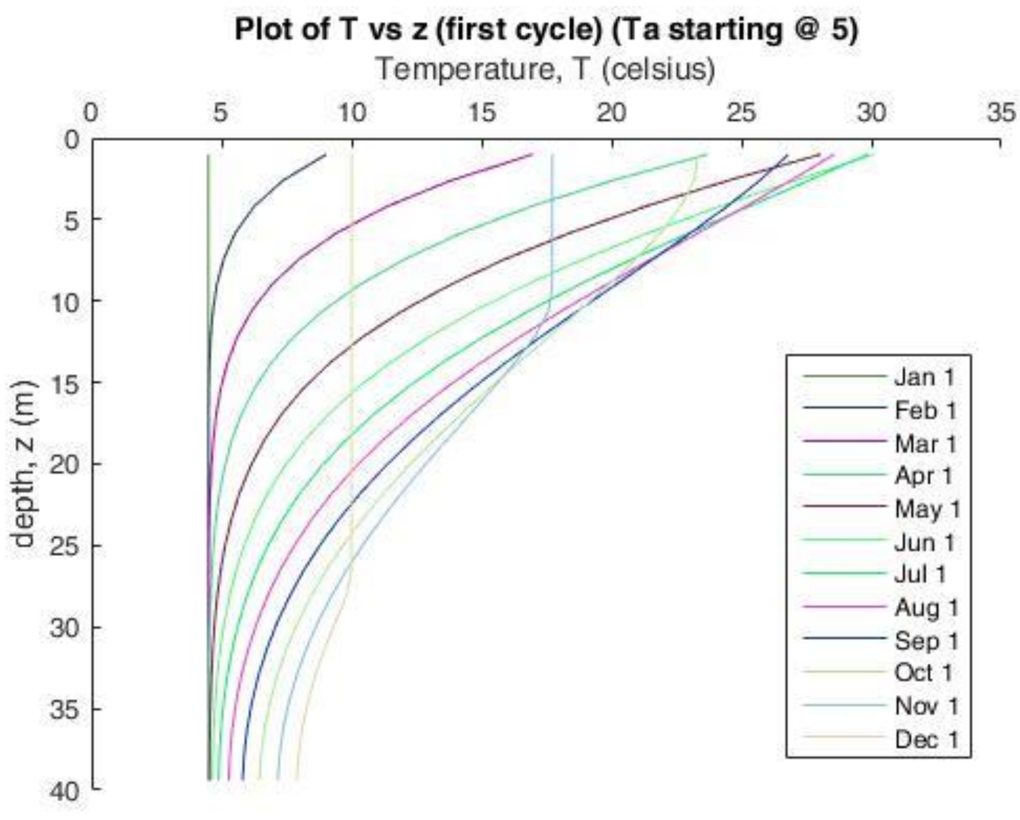

Figure 3.13 – Plot of Vertical Temperature distribution v/s depth (first cycle)

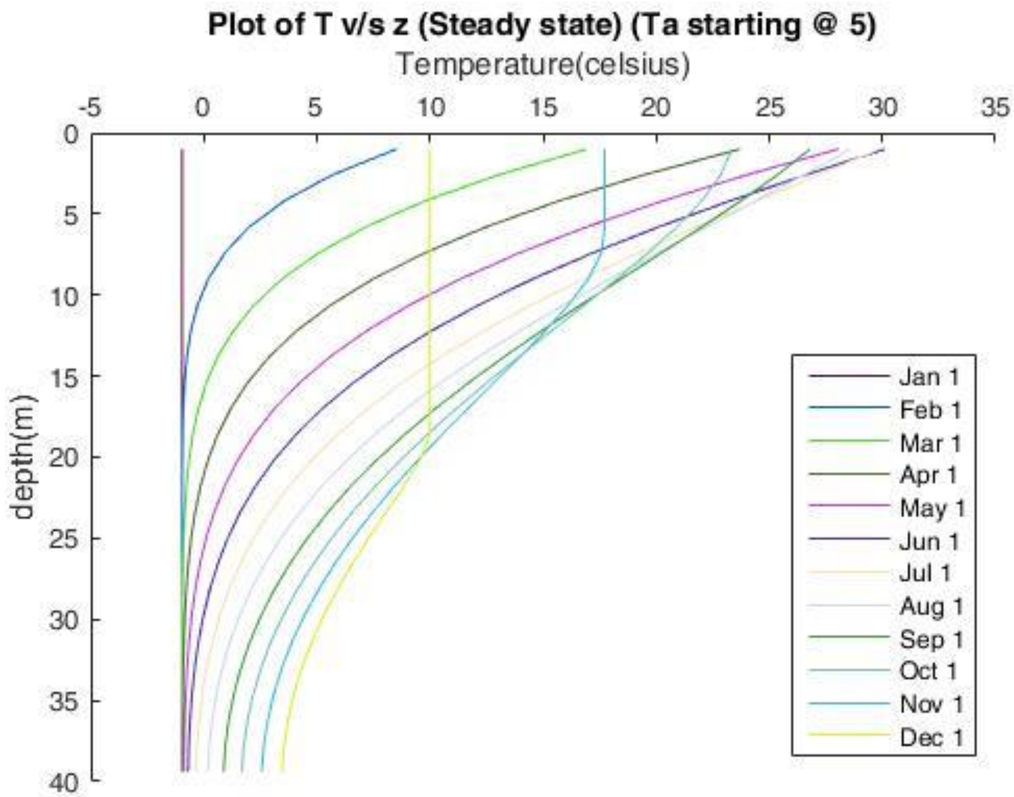

Figure 3.14 – Plot of Vertical Temperature distribution v/s depth after lake reaches steady state

From the temperature distribution obtained above, plots of surface and bottom temperature variation with time was plotted for 3 values of depth of the lake. In each case three different values of diffusivity were studied. In all the cases the variation in surface temperature was found negligible, however the bottom temperatures showed quite some variation. In the case of 40m depth of lake, the bottom temperature reaches higher values and also quicker since the onset of stratification for higher values of diffusivity. Results are shown in Figure 3.15. In the case of 70m depth of lake, the difference in the bottom temperatures is slightly evident for different values of diffusivity. Results are shown in Figure 3.16. In the case of 100m depth of lake, the bottom temperatures hardly change with variation in diffusivity.

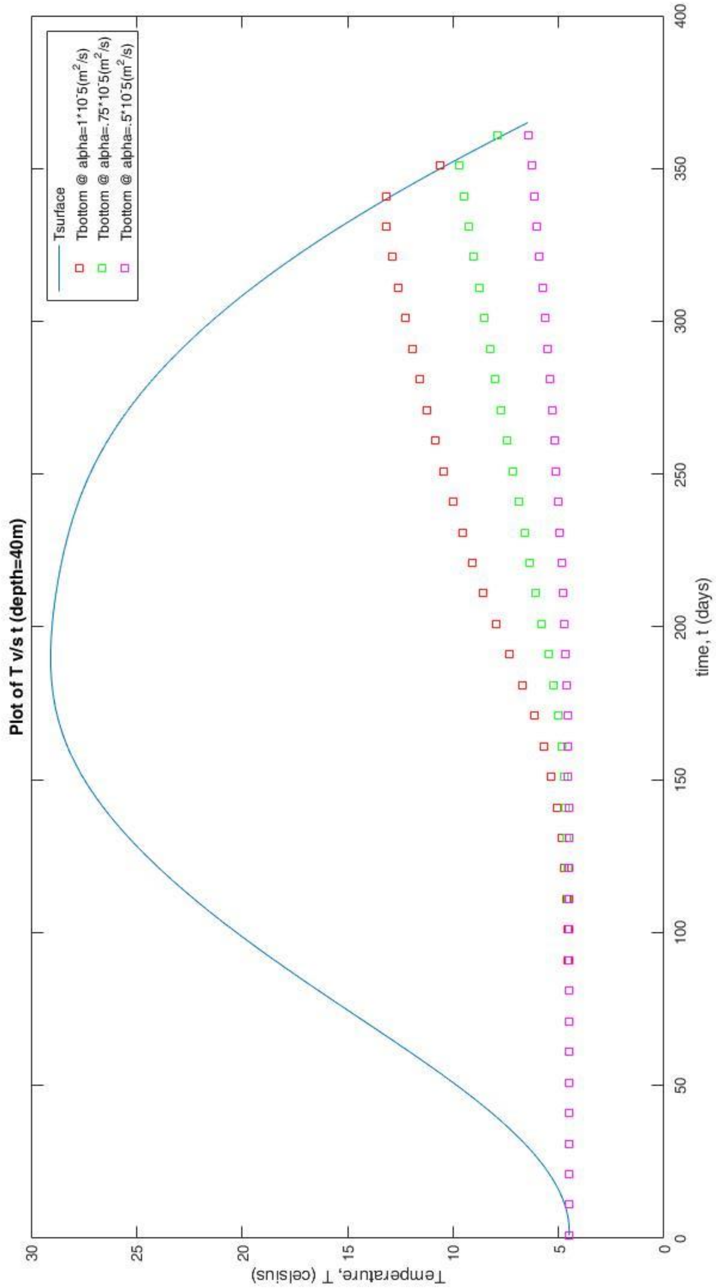

Figure 3.15 – Plot of Temperature v/s time for depth = 40m

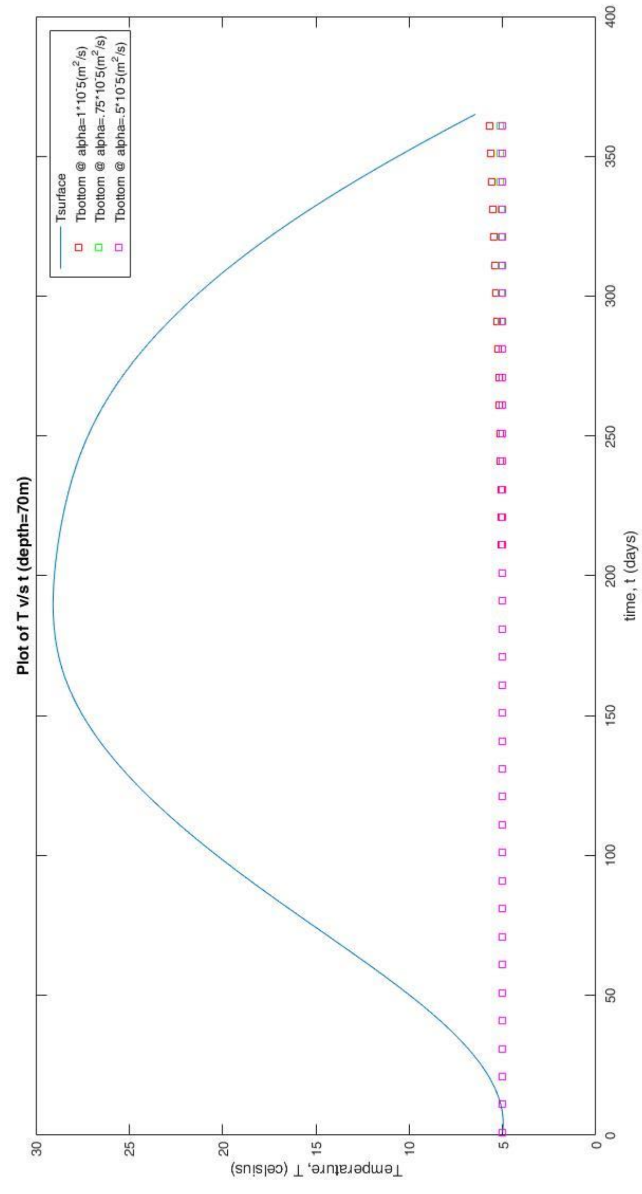

Figure 3.16 – Plot of Temperature v/s time for depth = 70m

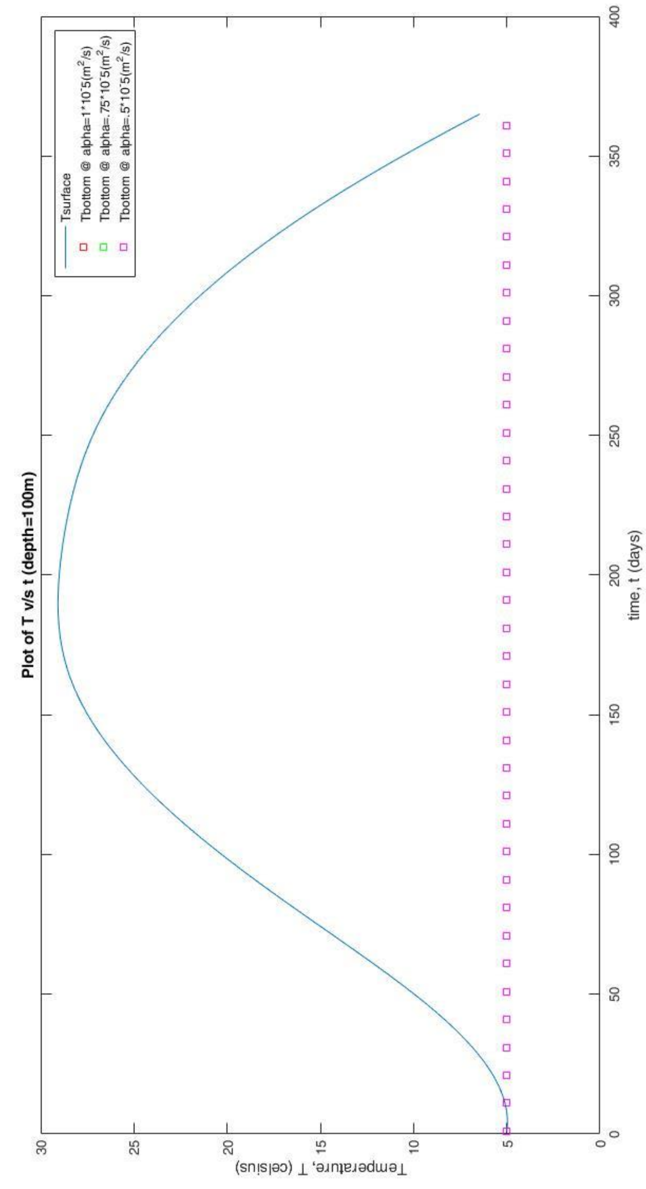

Figure 3.17 – Plot of Temperature v/s time for depth = 100m

3.4 EFFECT OF ATMOSPHERIC RADIATION FACTOR

The variation in surface and bottom temperatures with respect to ambient temperature was studied for 3 values of atmospheric radiation factor, keeping all the other parameters as constant. When the atmospheric radiation factor is 0.8 the peak surface temperature is almost about equal to the peak ambient temperature. Results are shown in Figure 3.18. When the atmospheric radiation factor is 0.75 entire curves of the surface and bottom temperatures drop down and the peak surface temperature differs from the peak ambient temperature by about 4^0C. Results are shown in Figure 3.19. When the atmospheric radiation factor is 0.7 entire curves of the surface and bottom temperatures drop way below and the peak surface temperature differs from the peak ambient temperature by about 8^0C. Results are shown in Figure 3.20. Higher surface temperatures for higher values of atmospheric radiation factor can be attributed to the large amounts of long-wave radiation being absorbed by the surface of the water.

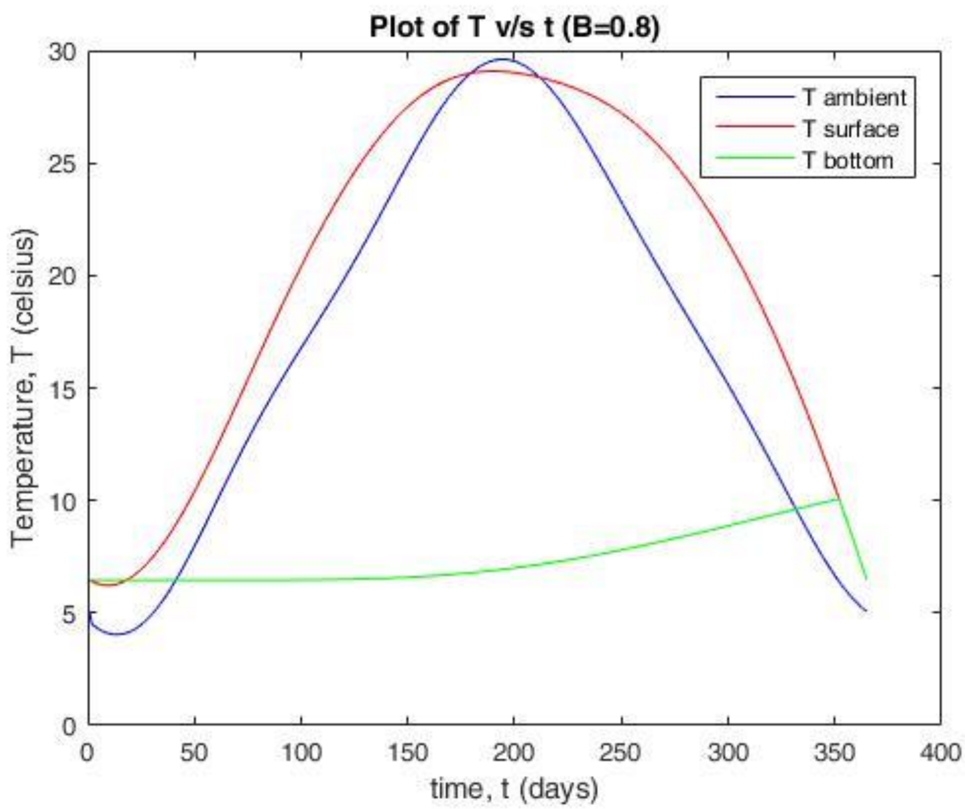

Figure 3.18 – Plot of Ambient, Surface & Bottom Temperatures v/s time for B=0.8

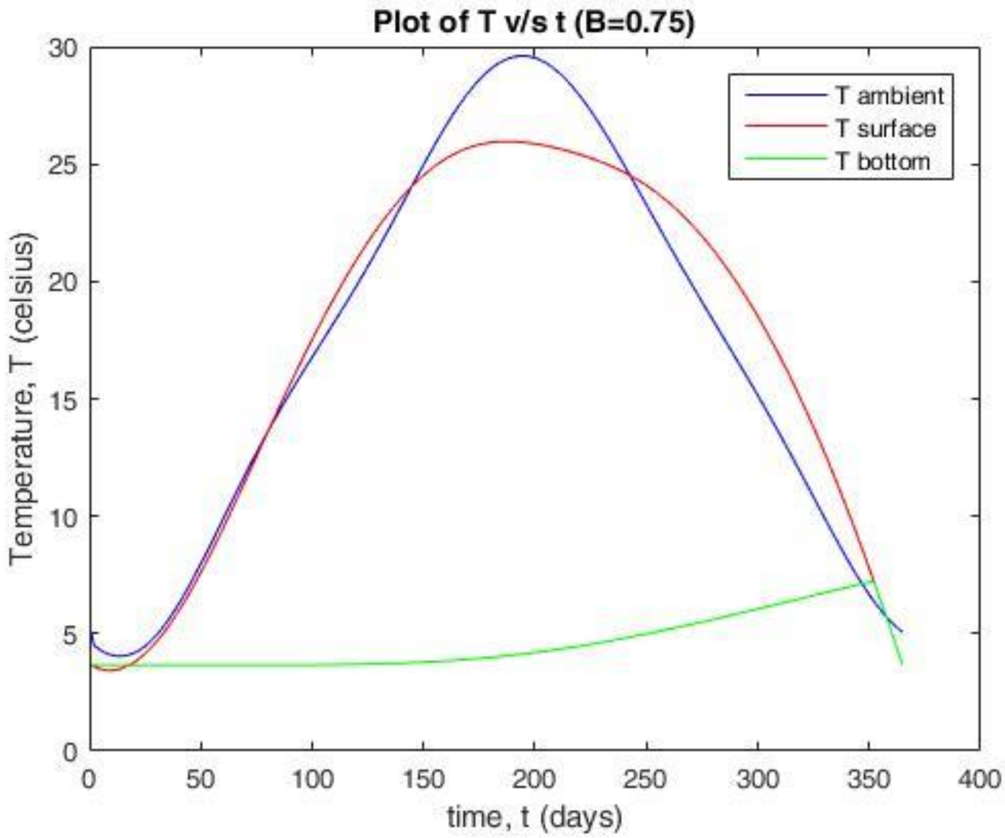

Figure 3.19 – Plot of Ambient, Surface & Bottom Temperatures v/s time for B=0.75

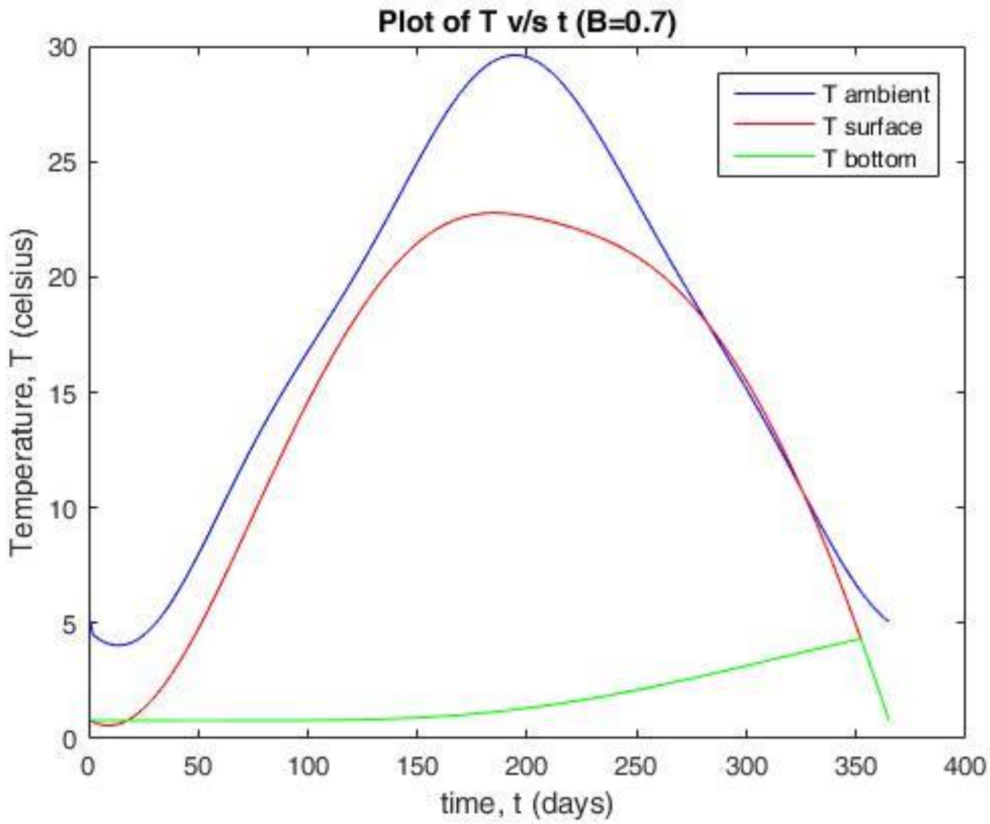

Figure 3.20 – Plot of Ambient, Surface & Bottom Temperatures v/s time for B=0.7

Finally, the effect of surface heat loss as a function of surface temperature was studied for various values of atmospheric radiation factor for various seasons. For all the cases, it was observed that the surface heat loss reduces with increase in the atmospheric radiation factor for constant wind speed of 10 km/hr because large amounts of long wave radiation are absorbed by the water surface. Also, for a given value of atmospheric radiation factor, the equilibrium temperature increases with increase in the ambient temperature. These seasonal variations can be seen in Figure 3.21, 3.22 & 3.23.

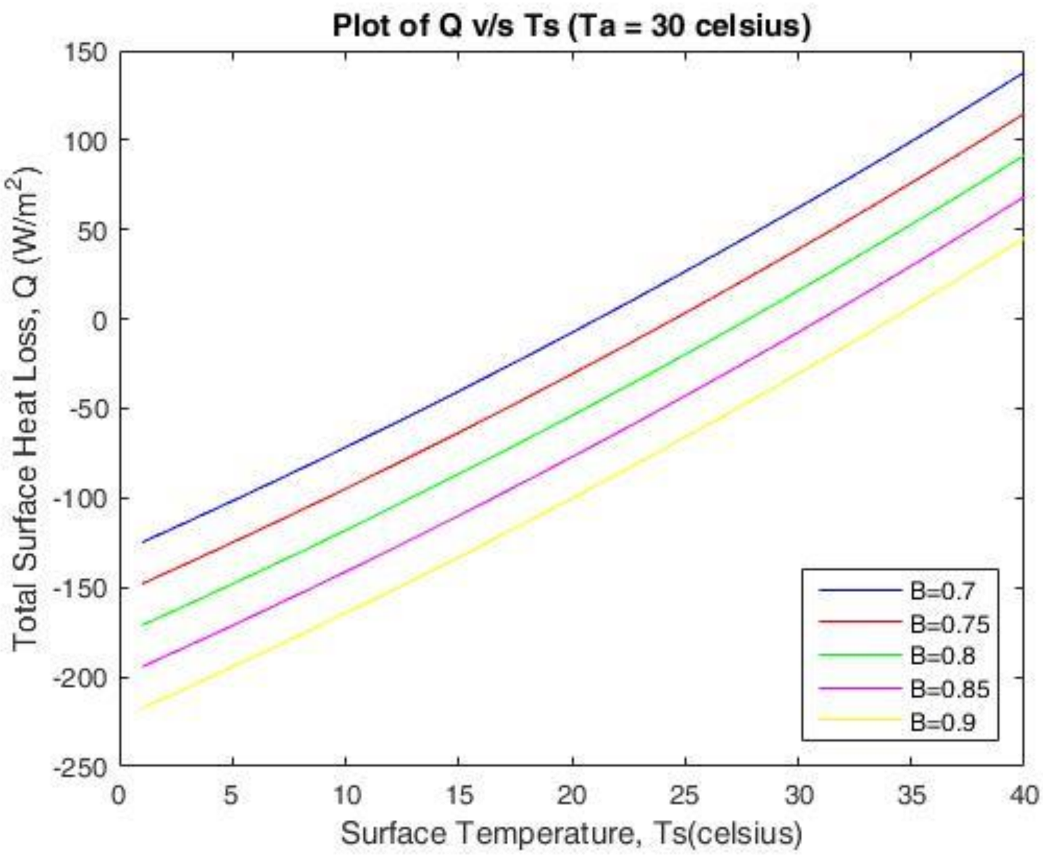

Figure – 3.21 Plot of Total Surface Heat Loss v/s Surface Temperature varying B (summer)

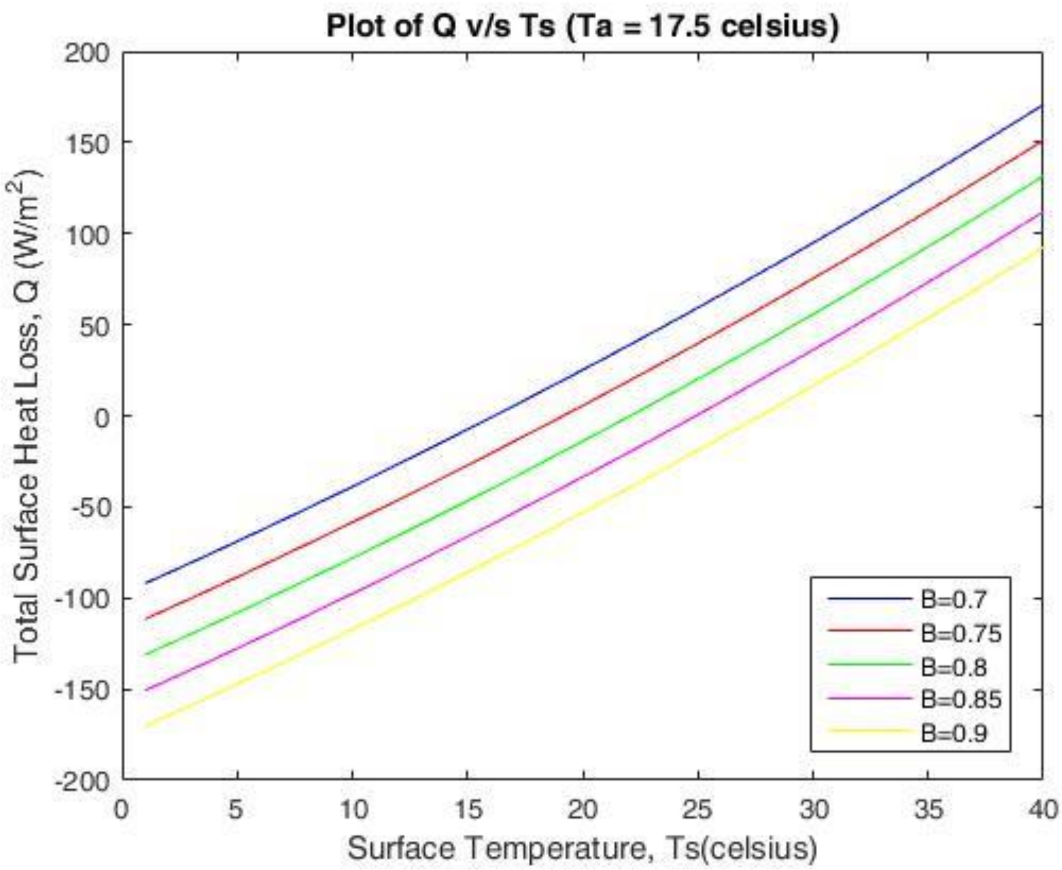

Figure – 3.22 Plot of Total Surface Heat Loss v/s Surface Temperature varying B (spring & fall)

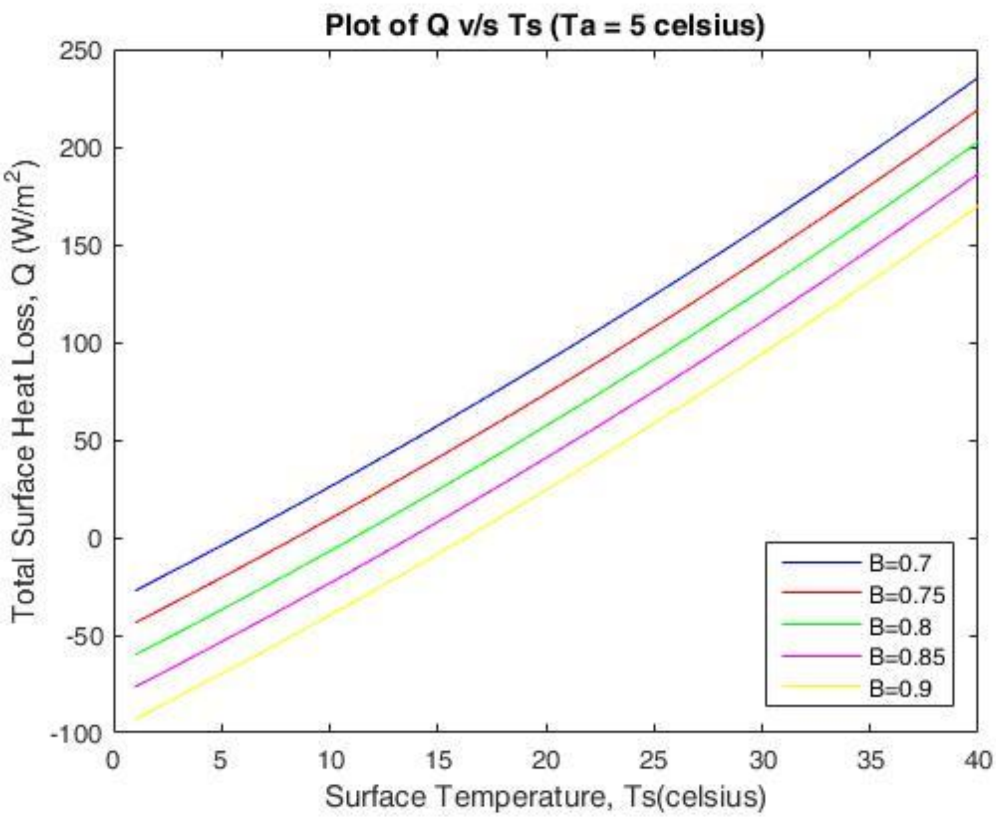

Figure – 3.23 Plot of Total Surface Heat Loss v/s Surface Temperature varying B (winter)

CHAPTER 4

CONCLUSIONS & FUTURE WORK

In the present work, primarily a general trend for periodic variation in ambient temperature during the year was determined using the weather data obtained for New Brunswick. This was done by developing a curve-fitting tool and the validity was checked by varying the starting temperatures on Jan 1st by ±5^{0}C. The same pattern was observed and thus this ambient temperature variation was considered for further calculations. The variation of net surface heat loss with water surface temperature was calculated for all the seasons. These figures were plotted for various wind speed values for each season. From each of these plots the equilibrium temperature i.e. the surface temperature at which the surface heat loss is zero was calculated and the variations of equilibrium temperature with wind speed and ambient temperatures were plotted. The results were comparable to similar earlier studies. The surface heat transfer coefficient was calculated using the gradient of the surface heat loss v/s surface temperature curves and the values were comparable to standard North American conditions for summer.

Using the above results and by employing the finite difference scheme, the surface temperature variation during the year was determined for different depths of the lake. It was observed that after completion of one complete cycle i.e. one year, the surface temperature goes lower and lower as the depth of the lake decreases. The shallower the lake, larger will be the variation in surface temperature between Jan 1st and Dec 31st. Also, lower the ambient temperature lower will be the surface temperature as expected. Using these results the iterations were run for various depths until the variation in surface temperature from one year to another was close to zero. This variation showed that after 4 years of complete cycle the lake reaches steady-state and thereafter the variation in surface temperature from year to year is considerably absent.

Once the steady-state surface temperature was studied, the transient monthly temperature distribution along the depth of the lake was determined for both the first cycle and after the lake reaches steady-state. The temperature profile indicates that the lake is in a fully mixed condition at the beginning of the year. As winter progresses the ambient temperature starts to drop and reaches a minimum value which makes the lake to start losing energy until the surface reaches the winter minimum temperature. After this the ambient temperature starts to increase and as a result the lake starts gaining heat through the surface which is slowly passed on to the lower layers. This begins the stratification in the layers of the lake. The surface temperature starts to increase rapidly as the year progresses but the temperatures at the lower depths increase gradually, since it only receives heat from the hot upper layers. This continues till the surface temperature reaches a maximum value in summer. During fall, the ambient temperature starts to drop and the surface of the lake starts to lose heat resulting in an isothermal top layer. The surface temperature reduces rapidly while the bottom layers slowly gain heat from the heated upper layers. The onset of winter de-stratifies the lake and it again becomes fully mixed at the end of the year with temperatures close to that at the beginning of the year and the cycle repeats until the temperatures reach steady-state. The effects of diffusivities for different depths were studied and it was observed that for lakes deeper than 70m, the effect of diffusivity on the temperature distribution is negligible indicating closer to steady-state behavior.

Finally, the variation of atmospheric radiation factor which is the driving factor for warming was studied keeping other parameters as constant. Higher values of atmospheric radiation factor reduce the heat loss due to back radiation and thus the total heat loss from the surface. This stores large amounts of incident radiation in the water body giving rise to increased water surface temperature and thus warming the local environment over time.

Using the results from this study, future work can be carried out to determine the temperature distribution by developing two-dimensional transient numerical models which will reflect the effects of turbulence in case of moving water bodies such as rivers. Experimental temperature observations can also be made to determine the validity of the present numerical model. Similar models can be developed taking into account heat rejection from power plants into water bodies and their effects on local warming. The temperature distribution for different depths of water bodies and different diffusivities can be studied for water bodies used for cooling power plant condensers. The present work considers no heat exchange at the surface and bottom, however future studies can be made taking into effect convection loss from the sides and bottom as well.

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APPENDIX

1. Equations and coefficients obtained from MATLAB for curve fit of Ta v/s t.

Ta starting at 5^0C

General model Sin4:

Ta = a1*sin(b1*t+c1) + a2*sin(b2*t+c2) + a3*sin(b3*t+c3) + a4*sin(b4*t+c4)

Coefficients (with 95% confidence bounds):

a1 = 17.61

b1 = 0.00188

c1 = 1.172

a2 = 11.22

b2 = 0.01729

c2 = 4.491

a3 = 66.03

b3 = 0.05734

c3 = 5.899

a4 = 66.79

b4 = 0.05728

c4 = 2.772

Goodness of fit:

SSE: 1.123

R-square: 0.999

Adjusted R-square: 0.9933

RMSE: 0.7492