CS(AR) 193

SEDIMENTATION IN THERMALLY STRATIFIED LAKES OF KUMAUN REGION

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INDIA
1995-96

PREFACE

The most important parameter for any water quality modelling of lake-water is the vertical profile of temperature which determines the thermal stability of a lake.

Sediments brought into the lakes from the nearby catchment by inflowing streams and overland flow have increased and is increasing mostly due to human interference in the catchment area of a lake. These sediments get deposited in the lake bottom subsequently depending on the temperature profile of the lake.

A simple methodology based on Stokes' Law has been suggested in the report to estimate the sedimentation rate for a lake for which comprehensive hydrological data are not available. Using the temperature profile, the methodology has been applied to three lakes in Kumaun region.

This report entitled "Sedimentation in Thermally Stratified Lakes of Kumaun Region" is part of the work programme of the Lake Hydrology Division for 1995-96 and has been prepared by Shri A.K. Bhar, Scientist-E.

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ABSTRACT

Sedimentation and consequent eutrophication of lakes are the two major problems of Indian lakes. Sedimentation processes inside a lake depends mainly on the temperature profile of the lake.

Comprehensive data about various limnological and hydrological processes related to lake sedimentation are few and far between and this poses a serious handicap to estimate the sedimentation rate. A simple methodology based on Stokes' law has been suggested in this report to have a first hand idea about the rate of sedimentation in a lake, if the temperature profile of the lake and sieve analysis results about the sediments are available.

The suggested methodology has been applied to three lakes (Bhimtal, Khurpatal, and Sattal) in Kumaun region of Nainital district, Uttar Pradesh. The lakes are warm monomictic with one circulation period during winter. The lakes get stratified with onset of spring in March. According to the calculation, for a difference of $10^{o}C$ between two depths in the water columns, the density difference would be 0.0018, suggesting quite stable thermal stratification. Destratification occurs in November and the lakes remain homothermal till the end of February. It has been observed that settling time of a sand particle and a silt particle are almost same for stratified and homothermal lake conditions for this region. However, in case of a clay particle, the settling time is more than that of sand and silt for both stratified and homothermal conditions.

1.0 Introduction

The most important physical/chemical/biological parameter for water quality modelling in lakes is the water temperature - and more specifically the vertical profile of temperature. The reason for the importance of the vertical temperature profile is its role in determining the stability of a lake over depth. The thermal stability determines not only the vertical exchange of energy but also of other nutrients. Stability determines the rate at which buoyancy forces dampen out the turbulent mixing induced by current shear. Thus greater the vertical temperature gradient (dt/dz), the greater the stability and the more restricted are vertical exchanges.

A lake is at or just above the temperature of maximum density around the time of the spring. Incoming solar radiation begins to increase such that there is a net available radiation. The excess energy is stored in the lake and is mixed downwards by wind-induced turbulence. This mixing is effective to the bottom of the lake for shallow lake. In other lakes, a layer of finite thickness forms defined by the limit of the effectiveness of this mixing. This layer, the epilimnion, deepens only during the summer period and the temperature of the epilimnetic temperature rises. The water at the bottom of the lake shows only marginal temperature increase. This is called as hypolimnion and can be defined as the lower layer in which the temperature gradient is negligible. There is usually a layer in between these two layers and is called the metalimnion in which the value of dT/dz is very large. This layer is also often called thermocline region, although the thermocline is more accurately defined as the depth at which $\partial^2 T/\partial z^2=0$. A typical temperature profile of a lake is shown in Fig. 1 (Henderson-Sellers, 1984).

The stratification persists for several months during summer heating period. However, in late summer, the net energy balance at the lake surface becomes negative and the lake begins to cool. The upper layers lose heat (by direct radiation, evaporation etc.) and an instability forms such that the upper most water is cool than the rest of the epilimnion. It is, thus, negatively buoyant and sinks. This process of convective overturn predominates until the lake becomes isothermal.

The major surface energy exchanges occur at the free surface of the lake. Although there is some energy flow into and out of the lake sides and bottom, this is seldom taken into account in calculating vertical temperature profiles. This is a valid approximation for deeper and larger lakes and certainly acceptable for smaller lakes which exceeds the dimensions of a pond.

Lakes in Kumaun and in valley of Kashmir are warm monomictic lake with one circulation period during winter. The lakes get stratified with onset of spring in March. According to the calculation, for a difference of $10^{o}C$ between two depths in the water columns, the density difference would be 0.0018, suggesting quite stable thermal stratification. Destratification occurs in November and the lakes remain homothermal till the end of February. (Bhatt and Pandey, 1991). Lakes in Rajasthan are also get stratified in similar manner (Saint et.al., 1994).

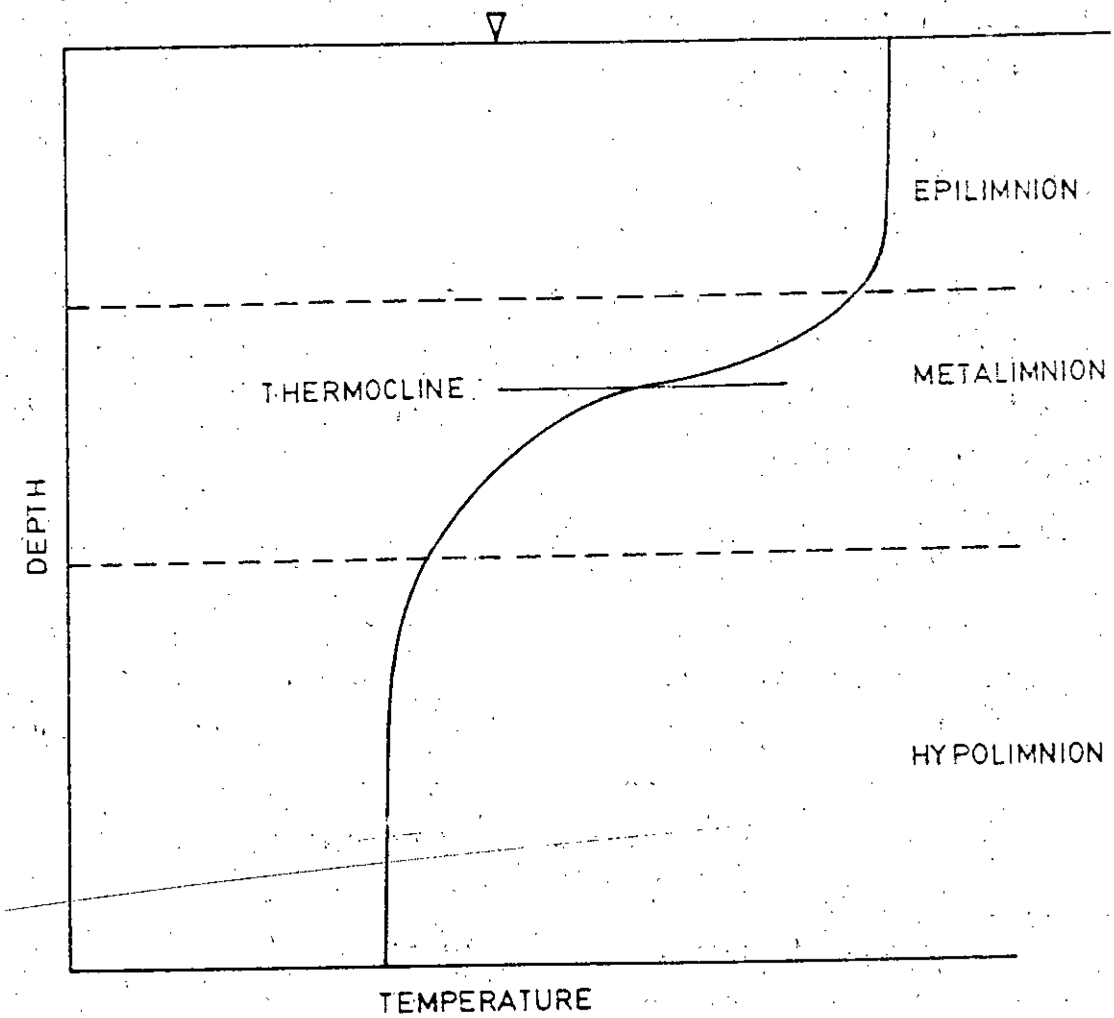

FIG. 1. TYPICAL SUMMER TEMPERATURE PROFILE IN A LAKE.

Due to the thermal stratification, there exist density differences among the different layers of water in a lake and the sediments coming from the adjoining catchment of a lake are influenced during sedimentation. In this study, a simple methodology on the basis of Stokes'law has been used to estimate the time taken for different types of sediments to deposit at the lake bottom. The sedimentation analysis have been applied to Bhimtal, Khurpatal, Sattal lakes of the Kumaun region in Nainital district of Uttar Pradesh.

2.0 Stokes' law

Stokes' law provides the terminal velocity of a spherical particle of diameter between 0.2 mm to 0.0002 mm in a body of still liquid which is indefinite in extent. Stokes' law is written as (Singh, 1967):

$$v = (2/9)r^2 \, (\gamma_s - \gamma_l)/\eta \qquad \ldots(1)$$

where v = terminal velocity of sinking of a spherical particle in a still fluid (when the particle starts sinking, its velocity increases at first under the acceleration of gravity, but within a few seconds it attains a constant terminal velocity.) (cm/sec).

r = radius of spherical particle (cm)

γ_s = density (unit weight) of particle (g/cm^3)

γ_l = density of the liquid (g/cm^3)

η = dynamic viscosity of the liquid (g sec/cm^2)

There are some limitations in the application of the Stocks'law. These are (Taylor, 1961):

1. The particles are never truly spherical. So, the sedimentation analysis gives the particle size in terms of Equivalent Diameter. The equivalent diameter is the diameter of a hypothetical sphere composed of material having the same specific gravity as that of the actual soil particle and which will settle in a given liquid at the same terminal velocity as the actual soil particle.

2. An average value of specific gravity of particles is used. The value for some particles may differ appreciably from the average value. But, this limitation is not of major importance.

3. The side walls of the container also affect the fall of particles near the walls. Therefore, it is desirable to have a fairly large container. For a lake, this limitation is overcome as the lake could easily be assumed as a large container of relatively still water.

Assuming that due to temperature stratification during summer, depth of a lake could be subdivided into a numbers of layers according to temperature profile as d_1, d_2, ..., d_n and the respective terminal velocities as computed by the Stokes' law are v_1, v_2, ..., v_n, respectively, then the time required, t, by a particle of particular size to deposit at the lake bottom is

$$t = d_1/v_1 + d_2/v_2 + \ldots\ldots + d_n/v_n \qquad \ldots(2)$$

If viscosity is given in absolute units of dyne sec/cm^2 (i.e., poise), it is to be divided by acceleration due to gravity (cm/sec^2) for substitution in Eq. (1). Density of water and viscosity of water at various temperatures are available (Singh, 1967). Density and viscosity of water for the range of temperature used in the present study are given Table-1 and 2.

Table-1. Density of water at various temperatures

Temperature (°C)	Density (g/cm^3)	Temperature (°C)	Density (g/cm^3)
10	0.999728	21	0.998021
11	0.999633	22	0.997799
12	0.999525	23	0.997567
13	0.999404	24	0.997326
14	0.999271	25	0.997074
15	0.999127	26	0.996813
16	0.998970	27	0.996542
17	0.998802	28	0.996262
18	0.998623	29	0.995974
19	0.998433	30	0.995676
20	0.998232	31	0.995369

Table-2. Viscosity of water

Temp. (°C)	Viscosity (Poise)	Temp. (°C)	Viscosity (Poise)	Temp. (°C)	Viscosity (Poise)
10	0.01310	18	0.01060	26	0.00875
11	0.01274	19	0.01034	27	0.00855
12	0.01239	20	0.01009	28	0.00836
13	0.01206	21	0.00984	29	0.00818
14	0.01175	22	0.00961	30	0.00818
15	0.01145	23	0.00938	31	0.00783
16	0.01116	24	0.00916		
17	0.01088	25	0.00895		

3.0 Sedimentation analysis using Stokes'law for Kumaun lakes

3.1 Description of the lakes

Sharma (vide Bhatt and Pande, 1991) studied the ecosystem and trophic status of three lakes in the Kumaun region. The lakes are: Bhimtal, Khurpatal and Sattal (Fig.2). It is reported that during the last two or three decades, there is unprecedented increase in human activities. Due to this, the lakes are passing through the different stages of limnological evolution including loss of storage ;due to sedimentation. Bhimtal and Sattal area is comprised of a group of sedimentaries consisting of phyllites, quartzites, and some calcareous quartzites. Khurpatal area is predominantly dolomitic. The lakes in the Nainital district of Kumaun are often referred to as the "Westmoorland of Kumaun" and are aligned NW-SE and lie along major dislocation zone. Bhimtal lake has only one drain. Khurpatal and Sattal have no perennial drain and only the runoff water enters all along hill slopes of the watershed with sediments. The climate of the area is characterised by long winters and short summers. The year could be divided into three season; viz., summer (March to June), rainy (July to Oct.) and winter (Nov. to Feb.). Some of the morphometric and hydrographic characteristics of the lakes are given in Table-3 (Bhatt and Pande, 1991).

3.2 Sedimentation analysis

As stated earlier, the lakes get stratified with the onset of spring in March. Destratification occurs in November and the lake remains homothermal till the end of February. All the lakes are warm monomictic type with fairly stable thermal stratification. Fig.3 depicts the thermal stratification of the three lakes during summer months (Bhatt and Pande, 1991).

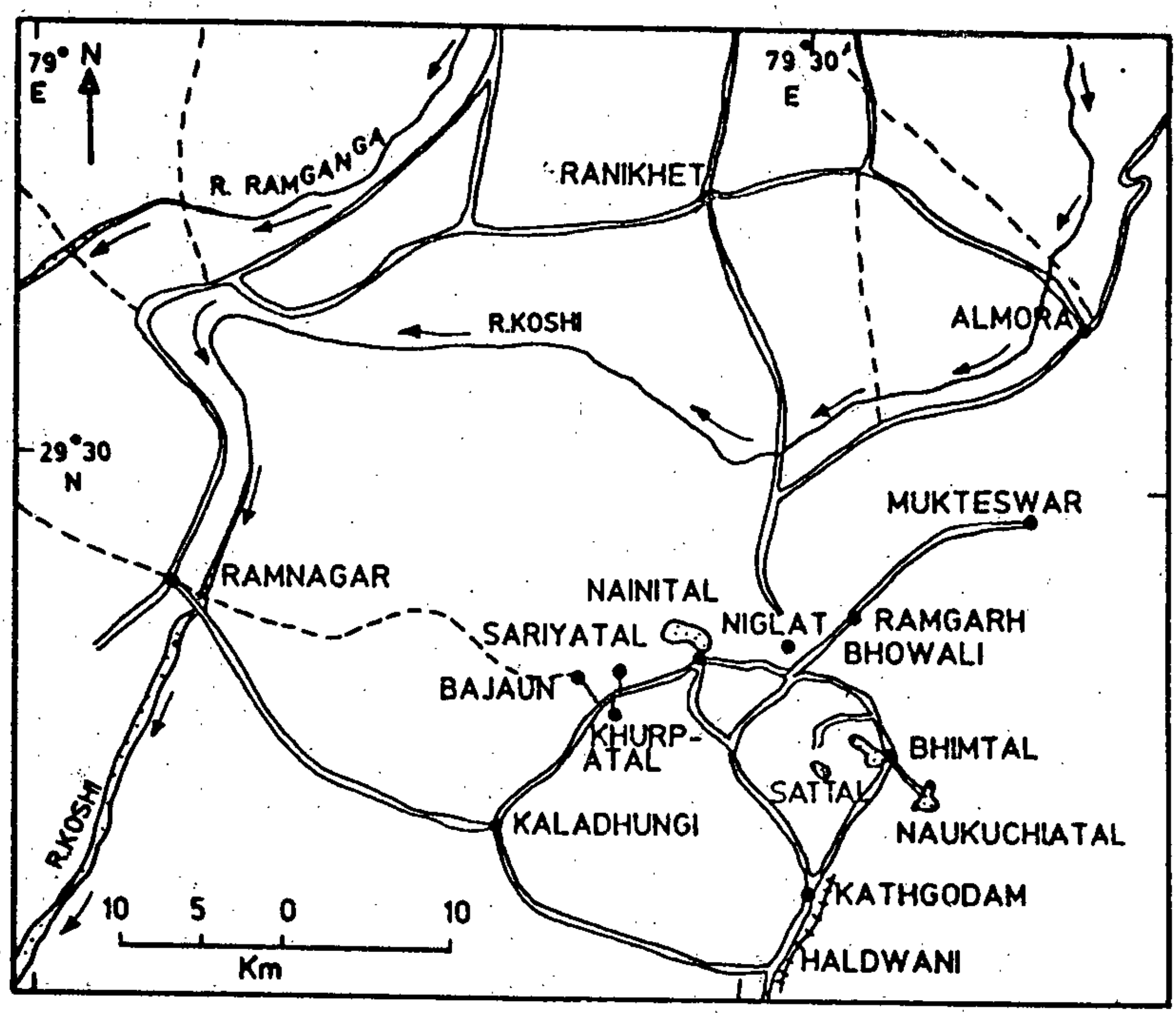

FIG. 2. MAP SHOWING LOCATION OF THE LAKES.

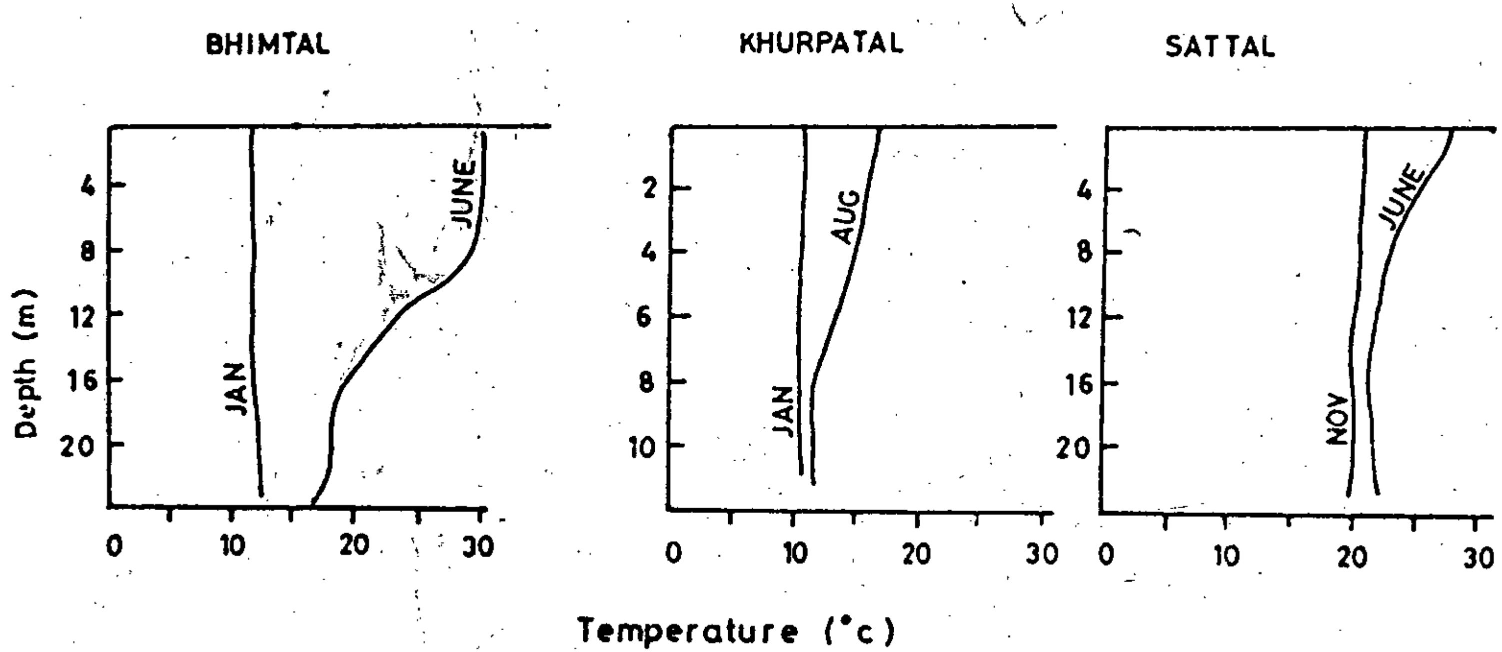

FIG. 3. TEMPERATURE PROFILE OF THE LAKES.

Table 3. Morphometric and hydrographic and other data of Bhimtal, Khurpatal and Sattal

Parameters	Bhimtal	Khurpatal	Sattal
Altitude(m)	1331	1600	1286
Longitude	$79^{o}36'E$	$79^{o}27'E$	$79^{o}32'E$
Latitude	$29^{o}20'N$	$29^{o}25'N$	$29^{o}21'N$
Length(m)	1974	-	830
Breadth(m)	457	-	200
Maximum depth(m)	25.8	12.0	20.0
Mean depth(m)	11.5	-	8.0
Surface area(ha)	72.25	13.0	-
Length of shore line (m)	4023	-	-
Catchment area (km^2)	11.4	-	3.32
Annual rainfall(mm)	1711	2000	1540
Temperature(^{o}C)			
Maximum	28.8	26.0	30.0
Minimum	1.5	1.0	1.6
Seechi transparency(m)	2.5	2.4	3.5
Euphotic zone(m)	12.5	10.0	12.0

From the perusal of thermal stratification plots (Fig.3) for the three lakes, the depth of each lake is divided in several layers and it is assumed that the temperature remains same throughout a layer. The numbers of layers in each lake and their corresponding temperatures are given in Table-4.

Table 4(a). Depth and thickness of thermal layers during the month of June for Bhimtal

Depth of the layer (m)	Thickness (m)	Temperature(°C) Stratified	Temperature(°C) Homothermal
0m to 8m	8	30	12
8m to 12m	4	27	(In January)
12m to 16m	4	22	
16 to 20m	4	19	
20m to 26m	6	18	

Table 4(b). Depth and thickness of thermal layers during the month of August for Khurpatal

Depth of the layer (m)	Thickness (m)	Temperature(°C) Stratified	Temperature(°C) Homothermal
0m to 2m	2	16	10
2m to 4m	2	15	(In January)
4m to 6m	2	14	
6m to 8m	2	13	
8m to 12m	4	11	

Table 4(c). Depth and thickness of thermal layers during the month of June for Sattal

Depth of the layer (m)	Thickness (m)	Temperature(°C)	
		Stratified	Homothermal
0m to 4m	4	26	20 (In November)
4m to 8m	4	24	
8m to 20m	16	22	

Three sizes of sediments are considered, viz., medium sand of size 1 mm, silt of size 0.01 mm and clay particles of size 0.001 mm. The density of all these sediments are taken to be 2.67 g/cm^3. The density of water has been appropriately taken from Table 1 according to the temperature of a layer. The value of dynamic viscosity is read from Table 2 and is divided by the value of the acceleration due to gravity in cm/sec^2 so that the unit of viscosity is in g sec/cm^2.

It is assumed that a particular size of a spherical shaped sediment has reached at the top of the lake surface. Time that will be required for the particle to reach the bottom of a lake is estimated using Eq.2 and the thickness and temperature of each layer being known (Table 4).

4.0 Results and discussions

Time required for a spherical particle to travel from lake surface to the bottom of the lake has been estimated for the three lakes for both stratified and homothermal conditions. Three types of particle, viz., sand, silt and clay are considered in the calculation. The results obtained are given in Table 5.

Table 5(a). Computed travel time for sand, silt and clay to deposit at the bottom of Bhimtal (Maximum depth = 26m)

Particle	Size (mm)	Settling time Stratified	Homothermal
Sand	1.00	27 secs	35 secs
Silt	0.01	3 days	4 days
Clay	0.001	305 days	405 days

Table 5(b). Computed travel time for sand, silt and clay to deposit at the bottom of Khurpatal (maximum depth=12m)

Particle	Size (mm)	Settling time Stratified	Homothermal
Sand	1.00	16 secs	17 secs
Silt	0.01	2 days	2 days
Clay	0.001	180 days	195 days

Table 5(c). Computed travel time for sand, silt and clay to deposit at the bottom of Sattal (Maximum depth =20m)

Particle	Size (mm)	Settling time Stratified	Homothermal
Sand	1.00	21 secs	22 secs
Silt	0.01	2.4 days	2.6 days
Clay	0.001	240 days	260 days

From Table 5, it is observed that as the size of the spherical particle decreases, the settling time increases. Further, the settling time is almost same for sand and silt particles for both the stratified and homothermal conditions of the lake. However, for the clay particle, settling time is more for homothermal condition. However, in general, settling time for a spherical particle of particular size will actually depend on the prevailing temperature variation in the lake water and the depth of a lake.

The proposed methodology to analyse sedimentation in a lake is too simple and naturally can not answer all the questions related to lake sedimentation. However, the methodology comes in handy to reasonably estimate the decrease in lake's storage over time due to sedimentation brought in from the catchment if the temperature profile of the lake and percentage distribution of different sediments are known, especially for lakes wherein the sedimentation and other hydrological measurements are not available. Sediments brought in from the nearby catchment area of a lake could be reasonably estimated from remote sensing and other ancillary data by using Revised Universal Soil Loss Equation (Pundir, 1996).

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