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SEDIMENTATION IN LAKES

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Preface

Man has a limnetic fascination inherent with him. Also lakes serve the community as a source of water for various purposes like drinking water, irrigation, hydropower and recreation. But, erosion and deposition begin to destroy lakes from the moment they appear. A lake is visualized as a settling tank into which all or most of the river load may come and rest. The inflowing sediment of the rivers raise the floor of the lake and the outflowing river, if any, lowers the rim through erosion. The catchment erosion and consequently the load in the inflowing river increase substantially due to deforestation, land amelioration and intensification of agriculture etc.

Both runoff and siltation in the lakes increase due to these reasons. Enrichment of nutrient as a consequence, influences the chemical and biological aspects of lake water which often lead to eutrophication.

With these things in view, this report is prepared to highlight various factors and hydrological parameters and their interaction and interdependence with lake sedimentation process. Understanding of these interactions and processes will help to devise a scientific strategy to reduce and delay lake sedimentation and thereby conserving the valuable water.

The report entitled "Sedimentation in Lakes" is part of the work programme of the Lake Hydrology Division of this Institute for 1993-94. The report is prepared by Shri S. D. Khobragade, scientist - B of the Division.

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Abstract

Sedimentation is one of the major problems the lakes all over the world are facing. The deposition of the sediments begin to destroy the lake the moment they appear. From the available information, although little, it can be concluded that the life of many Indian lakes is already severely affected by sedimentation.

This review note discusses in details the physical process of sedimentation in lakes besides describing the various factors, major and minor, controlling the process. River and wind are the major natural agents that carry sediments to the lake. Their deposition and movement is affected by various other factors either directly or indirectly through their effect on the circulation of the lake water. Morphology of the lake, climate of the region being the principle factors. The report also discusses the various existing methods for the estimation of sedimentation. Sampling is the most commonly used methods. Remote sensing and isotope techniques are the more advanced methods but have their limitations either practical or economical. An economic and efficient method for the estimation of bed load is yet to be developed.

Sedimentation has a profound impact on the quality of the lake water through the bio-chemical activities enhanced by the sediments. This has been discussed at length.

Looking at the poor status of the research on the sedimentation studies of lakes in India an urgent need is felt to attend to this problem for the preservation of these natural resources which would otherwise undergo an untimely destruction.

1.0 Introduction

1.1 General

Lakes are transitory features of the earth surface. Each lake has a birth, life and death related to certain geological and biological processes. It is said that lakes are "borne to die". The life expectancy of the lake, however, may vary from a short spell between two floods to millions of years.

Particulate detritus in lakes is derived from the settling of the remains of plankton produced in water (autochthnous detritus) and from external organic and inorganic debris (allochthonous detritus), which is transported to the lakes by fluvian and aeolian processes. A portion of the organic detritus decomposes as it settles and the rest, together with the inorganic particulate matter, is deposited as sediment. Erosion and deposition begin to destroy the lake the moment they appear. The inflowing sediments of the streams raise the floor of the lake and the outflowing stream, if any, lowers the rim through erosion.

Sedimentation is one of the major problems the lakes all over the world are facing. The reduction in the lake capacity and rate of sedimentation are indicators of the future development of a lake. Sedimentation in lakes depends on tectonic pattern, climatic conditions, lithology of sediments in the drainage area, geological, geomorphological features of the lake basin and hydrochemical conditions (Saarse, 1988). As a result of all these factors sedimentation problems in lakes vary from lake to lake and continent to continent. The sediment deposition rates of the Great Lakes are given in Table 1.

Table 1 Solids balance of Great Lakes (after Thomann et al., 1989)

Lake/ Region	Fine grain solids loading rate (g/m^2.yr)	Overflow rate (m/yr)	Solids conc'n (mg/l)	Net solids loss rate (m/day)	Sediment deposition rate (g/m^2.yr)
Superior	98	0.8	0.5	0.53	98
Michigan	69	0.8	0.5	0.38	69
Huron	109	3.4	0.5	0.58	107
Saginaw Bay	146	10.3	8.0	0.02	64
Erie					
West	3742	101.1	20.0	0.24	1740
Central	1414	66.8	5.0	0.59	1080
East	1658	146.5	5.0	0.59	1080
Ontario	229	11.0	0.5	1.22	224

Research on lake sediments really began towards the end of the nineteenth century. In Europe, lakes in Switzerland received the attention of scientists from the mid-nineteenth century with early work concerned with water circulations and chemistry and then latter with the lake sediments themselves (Matter and Tucker, 1978). Prof. F. A. Forel, a Swiss naturalist, is the pioneer to initiate lake water quality study by publishing a paper describing the bottom fauna of lake Geneva in 1869 which infact marked the beginning of the scientific study of the lake (Reid and Wood, 1976). In north America, classic work was carried out by Russel and Gilbert towards the end of the nineteenth century. Studies of the lake sediments also had an important bearing on the evolution of the concept of the turbidity currents (Matter and Tucker, 1978). Since then, there has been an increasing interest in lake sedimentation studies. In India the status of the research on lake sedimentation is unfortunately very poor. As a matter of fact almost no work has been done so far on the physical aspect of the study. Some papers do deal with the chemical part of it. But according to Khanka (1991), Krishnan (1982), Wolstencroft et al., Zutshi (1987) and James et al. (1992), Kolleru Lake; Andhra Pradesh, Deepar Bheel; Assam, Sultanpur Jheels; Haryana, Renuka Lake; Himachal Pradesh, Dal Lake, Halgam Rakh Lake, Hokarsar Lake, Mirgund Lake, Shallabugh Lake, Wular Lake, Dihalia Jheels; all in Jammu and Kashmir, Pookot Lake; Kerala, Harike Lake; Punjab, Sambhar Lake; Rajasthan, Nainital Lake; U. P. etc are some of the lakes which are facing the problem of sedimentation, though the nature and the degree of the problem is not exactly known in most of the cases. Many of these lakes have become shallow due to excess siltation and accumulation of plant debris. The area of Dal Lake has shrunk from 23.4 sq. km to 13.82 sq. km in 118 years. With the present rate of siltation Dal Lake is expected to be converted into a marshy land or swamp in 70 - 80 Years (Raza et al., 1987). The depth of Renuka Lake has reduced considerably from 25 meters at the time of formation to a present depth of 13 meters only due to siltation and filling by landslide debris (Singh et al, 1991). A progressive reduction in the capacity; from 31,700 cu. m in 1899 to 26,200 cu. m in 1979 (5500 cu m in 80 years), obviously due to accumulation of sediments has been reported for Nainital Lake (Valdiya, 1988). The depth of Nainital Lake has reduced from 28 meters in 1922 to a present depth of 24.2 meters due to sediment accumulation. The rate of reduction of the capacity of the lake is 69 cu. m per year implying that the lake will be filled up completely in 380 years if the present rate of erosion were to continue unchecked. Significantly, the rate of sediment filling was 67 cu. m per year during 1969-1979, the maximum deposition taking place at the rate of 16 cu. m per year in the depth level of 10-15 m of the lake water (Valdiya, 1988). Sharma (1981) and Hukku et al (1974), however, had given life of 314 and 350 years respectively for Nainital Lake earlier (Valdiya, 1988). The sedimentary features of Dal Lake are presented in Table 2.

Table 2 Distribution of detritus and mineral grain in the sediment of Dal Lake (after Zutshi, 1987)

Basin	Depth (m)	% by volume		
		Coarse detritus	Fine detritus	Mineral grain
Hazratbal	4.2	54	6.8	29
Boddal	1.3	54	33.0	2
Nagin	5.2	23	56.0	10

Due to undesirable nutrient inputs many lakes have changed from oligotrophic to eutrophic stage for instance the Naukuchia Tal Lake (Kireet Kumar et al., 1992). Many undesirable changes in the structure of biological communities have also resulted and some important species have either declined or completely disappeared as in Dal Lake (Zutshi, 1987).

If proper control measures are not taken to check the increasing sedimentation problems of these lakes these valuable natural resources of water are bound to be destroyed for ever, causing a great social and economical loss. The matter is of great concern and needs serious attention in order to conserve the water for the community without much delay.

1.2 Importance of Sedimentation

Lakes contain about 95 % of the world's total fresh water (Scott, 1989). Lake waters are used for variety of purposes like drinking, power production, irrigation etc. Lake sedimentation, through its detrimental effects such as reduction in storage capacity, degradation of the water quality etc hampers the use of the lake water for such purposes. The impact, however, depends upon the degree of sedimentation and the characteristics of the lake deposits. Reduction in the storage capacity of the lake increases the probability of the flood as the cushioning effect of the lake decreases. It also affects the capability of the lake to regulate discharges of supplemental water in time of low river discharges for environmental protection and for industrial or agricultural activities. Sedimentation affects the chemical balance of lake water rendering it unsuitable for human consumption. The conduits of the irrigation systems may get chocked due to silt deposition causing the reduction in the efficiency of the system. In case of industrial use it may cause clogging of the heat exchangers in factories.

Sedimentation not only affects the hydrologic behaviour of the lake but also affects the chemistry, biology and the thermal characteristics of the lake water. High concentration of suspended matter may result in low primary production because of restricted light penetration. The availability of dissolved oxygen may be limited due to high sediment oxygen demand either by COD or BOD. Cooper et al. (1980) report that increased sediments alone reduced photosynthesis in Lake Tahoe. The presence of high suspended sediment concentration may adversely affect respiration and may also result in the burial of existing substrates (UNESCO, 1983). Benthos and fish are affected not only by the suspended sediments but also by modification of habitat caused by depositional sediments (Cooper et al, 1980). Supply of excess nutrients to the lake through the sediments, however, increases its productivity and although lakes begin as oligotrophic water body they are rendered eutrophic due to increase in the productivity level. This increasing productivity causes increase in the plant population especially the algal population. Eutrophication causes deterioration of lake water quality. The toxic contaminants transported by sediments also aid in the deterioration of the water quality.

The chemical and biological activities of sediments produce heat, contributing to the heat budget of the lake. Especially in lakes under the ice covered conditions, sediments are the major contributors of heat to the lake.

Sedimentary processes cause changes in the basin forms. The basin changes caused by sedimentary processes include the basin wide effects which are related to expansion or shallowing due to the natural erosion - accumulation trends and local changes which affect only part of a basin such as the migration of deltas, formation of spits and bars or modification of inflow due to drainage change (Sly, 1978). Sediments inflow to the lake, if substantially high, can even cause the simplification of the irregular morphology of the lake. If the morphological simplicity increases the water circulation patterns become modified leading to the changes in the sediment distribution patterns (UNESCO, 1985).

Sedimentary processes in lakes especially near the shores play an important role in the formation of new lakes. Smaller lakes are cut off from the larger parent lake by the formation of spit or bars due to transport and redistribution of clastic sediments. Different lake basins can also be formed when spits join through lakeward growth from apposite shores (Zumberge and Ayers, 1964). In Minnesota, Bulk Lake was thus cut off from the parent Cars Lake (Reid & Wood, 1976). Lake Nabugabo on north east coast of Lake Victoria in Central Africa was also formed in this manner (Walton, 1970). Fluvial processes creating lakes may produce oxbow and levee lakes as a result of channel shifting or by deposition of sediment barriers.

Sedimentation is mostly a problem for the lakes. But it can sometimes be a cause of availability of various useful and rare minerals and materials such as china clay (kaolin), iron (generally in the form of limnolite) and Keisulguhr (a diatamaceous earth) in the lake which may be of high economic value. Lake sediments may also contain oil and gas fields in their marginal sands and oil shales and evaporites in their centres (Selly, 1970).

Nearly all modern lakes have been affected by the activities of our high energy industrial civilization and by increasingly large number of people. Lake bottom sediments are valuable archives that preserve the records of the impact of the people on lakes and allow the preindustrial conditions to be determined. From the study of the physical, biological and chemical properties of the sediment cores, the most relevant changes occurring within the lake and its watershed can be recorded.

Lake sediments play an important role in helping to elucidate many processes occurring within the total lake system, including its surrounding surface and ground water drainage basins. Lake sediments play an important role in the dynamics of lake system as well. Recycling of mineralized organic matter especially the nutrients, in sediments by organic decay and pore fluid transfer processes are essential components of models describing the nutrient dynamics of lake system (Jones et al., 1978). Physical processes like waves, currents act to transport and sort minerals. Studies of the size and the mineralogic distribution of particulate sedimentary matter yields a time integrated picture of the major transport system within the lake. Mineralogical studies of the minerals of the external source (allogenic) yield useful information about the bedrock and the surficial geology of the drainage basin, weathering, the relative importance of the various inputs and the quantitative estimates of cultural loading on the lake systems. The mineralogy and chemistry of the lake sedimentary minerals derived from the internal source (endogenic) can be an important indicator of the processes of mineral precipitation within the lake (Jones et al., 1978).

The distribution of the sediments in the saline lakes is controlled by tectonic setting and climate and thus their deposits take on an importance beyond their size in the geological column (Hardie et al, 1978). To exploit this aspect of the saline lakes an understanding is needed of their sedimentary record. By recognising from the sedimentary record, which subenvironments were present and how they were arranged in space and time, one can interpret the history of a saline lake basin, either modern or ancient.

From lake management point of view, lake sedimentation studies are of utmost importance. The response of the lake to climatological or manmade changes is recorded in its sediments, in their composition and in the rate at which they are accumulating. Lake sedimentation studies help in linking the various factors which influence the sedimentary processes of the lake making it easy to understand how and under what circumstances they may be characterized. Further, the relationship between the particle size, composition and the geochemical behaviour, if developed, can be helpful to gain a proper appreciation of the role of the lake sediments in the hydrologic cycle of the lake systems.

2.0 Physical process of sedimentation

2.1 General

Water and wind are the main natural agents which bring sediments into the lake from outside. Suspended inorganic matter entering the lake from rivers and other external sources originates from the weathering and erosion of rocks which are composed of a number of minerals forming the main material of earth's crust. Water discharge to a lake is determined largely by climatic condition but, factors such as relief, vegetation cover, agricultural activity and the nature of the underlying rocks are also important. The discharge rises or falls with precipitation or snowmelt in the catchment.

Lake sediments are made up of variously sized rock fragments and soils ranging from clay and silt to sand, gravel and boulders, chemical precipitations and compounds including marl, tufa, ferric hydroxide, ferric carbonate and silicon dioxide and deposits such as peat or ooze. Coarse sediments are commonly found in lakes. As a rule the larger sized particle are found in the shallow zones while clay and silt may occur over any part of the bottom at any depth.

In strong flood flows coarse bed load material is mobile but in lesser currents the largest particles remain unmoved and only finer material migrate along the bed. Fine silts and clays are maintained within the water mass as it flows towards the lake. The fine particles have low settling velocities and are kept in suspension by the turbulent motion. Whereas the coarser particles move only while currents or bed shear exceed local threshold values, the very fine sediment moves whenever the water is in motion. Suspension concentration vary through discharge events. The actual concentration levels encountered depend upon the rainfall intensity and the susceptibility of the soil material for entrainment. In general, more flashy the stream the higher the suspended concentration carried (UNESCO, 1985).

The formation and behaviour of lacustrine sediments is dominated by the interaction of a number of physical processes whose relative importance is influenced particularly by the form of the basin, its orientation and size, and by the climatic conditions. The range of lake types and their sedimentary characteristics are widely diverse. Despite apparent differences, however, it is important to realize that essentially the same relationship may be used to express sediment response to dynamic forces in almost all the lake systems (Sly, 1978).

In saline lakes (lakes with more than 5000 ppm dissolved solids) (Hardie et al., 1978), totally different conditions prevail compared to the fresh water lakes. These lakes posses no outlet and the only means of removal of water is by evaporation. Consequently all material brought in by rivers must remain in the lake and the concentration of the dissolved substance gives rise to extensive chemical deposits (Hatch et al., 1965). The sedimentary features typical of the perennial saline lake are the saline mineral laminae and the thin beds with clastic sediments (mud) partings. Saline lakes in the wind blown dune field subenvironment are vulnerable to wind erosion deposit. They are characterized by aeolian deposits. To give a detailed account of description of the sedimentary processes and features of the sediments of different saline lake environments is beyond the scope of this report. However, Hardie et al. (1978), Eugster et al. (1978), Glennie (1970) and Reineck & Singh (1975) can be referred for the same.

2.2 Sedimentary classification of lake bottoms

Fine material from lake bottoms is eroded and brought into suspension from the influence of waves and currents. The shallow bottoms from which fine loose material is stirred up at every storm and where there are no extended periods of deposition are called erosion bottoms. Areas of transportation prevail where fine material is deposited but where erosion takes place during severe storms. These areas are called transportation bottoms. Areas where fine material is deposited and erosion never occurs are called areas of accumulation or accumulation bottoms. The limit between fine and coarse material is suggested to be 0.006 mm. Areas of erosion are characterized by hard and consolidated deposits, the bottom material is coarse. The deposits within areas of accumulation are fine and loose with high organic content, while the sediments within areas of transportation are diverse (Bengtsson et al., 1990).

In shallow lakes there are no accumulation bottoms where material can deposit. The bottom sediments close to the shores as well as in the central parts of such lakes are a mixture of fine and coarse material in contrast to lakes with definable accumulation bottoms (Bengtsson et al., 1990).

Fig. 1 shows the relation between the type of bottom, water depth and effective wind fetch (the distance over which the wind blows and transfers energy to the water to build up wind waves).

2.3 Movement and deposition of sediments in lakes

As a general rule, the water of a lake basin is

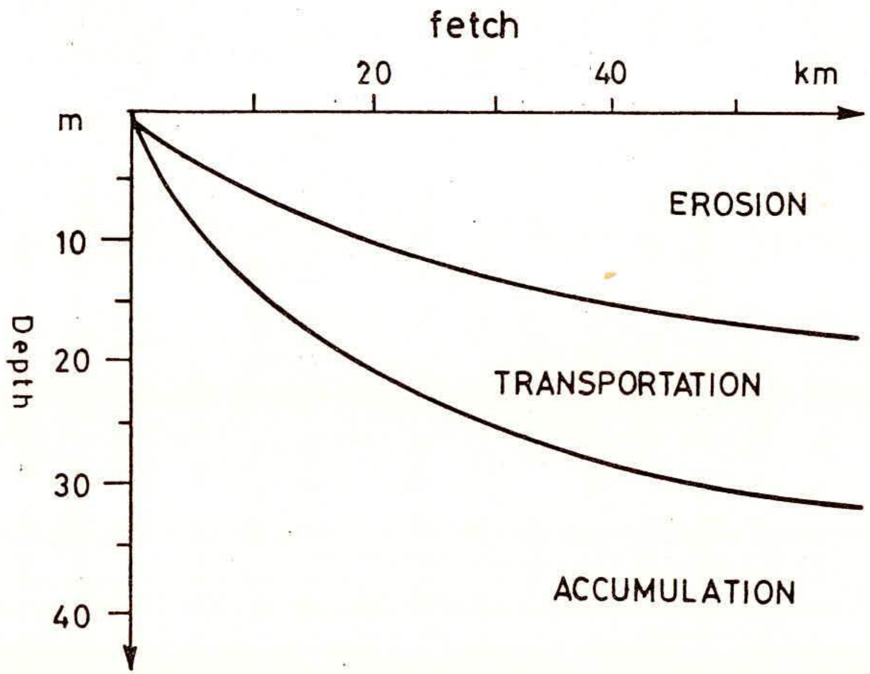


FIG.1– Bottom conditions as function of wind fetch and depth
(after Bengtsson et al.,1990)

partially or wholly in motion. This movement derived from either the internal or external forces, or both, is responsible for the movement of sediments inside the lake. The interaction of many physical and dynamic forces is involved. Three natural sources of energy controlling the physical processes are active in waters viz. wind, river inflow and solar heating (Table 3). These forces cause circulations in water which influences the rate of accumulation of sediments by determining the areas of scour, movement and deposition of sediments. Circulation not only causes suspension of sediments but also the resuspension. It also influences many sedimentary properties and can control the stability of deposits, the diagenesis of deposits and the preservation or destruction of primary sedimentary structures (Gorseline, 1985).

Table 3 Physical processes affecting sediment movement in lakes (after UNESCO, 1985)

Natural Agency	Wind	Solar Heating	River Input
Controls	orientation size,depth shape of basin local topography duration Coriolis force	latitude altitude local topography water depth	water dicharge sediment concentration water temp. coriolis force
Responses	wave generation water currents upwelling coastal jets seiches	stratification mixing overturn ice cover internal waves	turbid flumes density flows delta growth

Sediments brought into a lake are initially deposited preferably on shallow water near the shores. When the shear at the bottom exceeds a critical shear stress, the bottom is scoured. The critical shear stress depends on the properties of the bottom material (Bengtsson et al., 1990).

Bengtsson et al., have given the following relationship between bottom shear stress and bottom velocity,

$$\tau = f \rho u^2/2 \qquad \text{........(1)}$$

where,

τ = bottom shear stress,

ρ = density of water,

u = bottom velocity and

f = friction factor, which depends on the flow and the roughness of the bed.

Newly deposited material is brought into suspension easier than material, which has been compacted over a long period.

The change in the concentration of suspended solids in water depends on the difference between the rate at which erosion takes place and the rate of deposition. The deposition flux is usually assumed to be proportional to the concentration of suspended solids. If during a storm all fine loose material is eroded, then as the storm continues the erosion rate equals the deposition rate on erosion and transportation bottoms and in a shallow lake there is no net sedimentation. Usually erosion takes place only over a limited area of the total lake bottom area.

From shallow nearshore bottoms the material is often eroded, but since resuspension occurs often, there is only little amount of material to bring into suspension. Further out from the shore line, the bottom is scoured may be only once a year, but all the material that has settled during a year can be resuspended. The annual resuspension from this bottom may exceed the annual resuspension from the nearshore bottom (Bengtsson et al., 1990).

Resuspension of the bottom sediments proceeds through long periods of the year. It is not restricted to short periods of holomictic circulation. Even when lakes are thermally stratified resuspension proceeds in the lake with the result that sediments from the shallow portion of the lake get circulated over the entire lake. This is not only true for shallow lake but for deep lake also. In shallow lake the difference in magnitude of the seasonal resuspension appear to be related to lake morphometry (Nuhfer, 1985).

2.4 Role of wind

Wind plays an important role in sediment distribution in the lake. They affect sedimentation in small depositional basins and at times strongly influence sedimentation rates and stratigraphy. According to Johnson (1980), sedimentation focusing in the deepest regions of lake basins is probably caused primarily by sediment distribution by waves.

When wind blows across the lake, its velocity increases because of the change in land-lake frictional characteristics. Wind exerts a shear stress on the lake water surface and the resulting momentum transfer causes the surface water to move in the direction of the wind. What portion of the wind stress produces the mean water flow in a lake still can not be estimated mathematically but wind induced surface current is estimated to be 1 - 3 % of the wind velocity. The percentage varies as function of wind velocity, lake dimension, turbulence, lake thermal stratification and bottom conditions (Kuusisto, 1985). Waves, water surface currents and associated counter-currents, and the circulations (deflected to the right in the northern hemisphere by Coriolis force) (Fig. 2) are established. As a result of wind shear, water movements such as upwelling and coastal jets also develop in lake basins and have the capacity to selectively transport finer particulates of silt and clay size.

Wind generated waves follow elliptical orbital motion (UNESCO, 1985). When the waves run into shallow water, their horizontal motion components are maintained while the vertical components decrease untill ultimately the deformed circulation paths cease to close and mass movement of the water takes place (UNESCO, 1985). Wind generated waves follow oscillatory motion. The oscillatory currents ensure that the deposited sediments are frequently reworked in water shallower than half the wavelength. While fine sediment may be resuspended, sands remain on the bed.

The depth to which sediment transport occurs and the maximum grain size that can be moved by passing waves can be determined once the size of the wave generated (i.e. wave height, wavelength and wave period) is determined. Johnson (1980) has given graphs for determination of wave size (Fig. 3).

Following empirical equations (Johnson, 1980) are used to find out the sediment grain size D, moved by the passing waves:

$$\rho u_m^2/(\rho_s - \rho)\, gD = 0.46\,\pi(d_o/D)^{1/4} \quad , \text{ if } D > 0.5 \text{ mm} \qquad \ldots\ldots\ldots(2)$$

and,

$$\rho u_m^2/(\rho_s - \rho)\, gD = 0.21(d_o/D)^{1/2} \quad , \text{ if } D < 0.5 \text{ mm} \qquad \ldots\ldots\ldots(3)$$

where,

ρ_s = sediment grain density (approx. 2.6 g/cu. cm)

ρ = water density (approx. 1.0 g/cu.cm)

u_m = maximum horizontal velocity associated with the

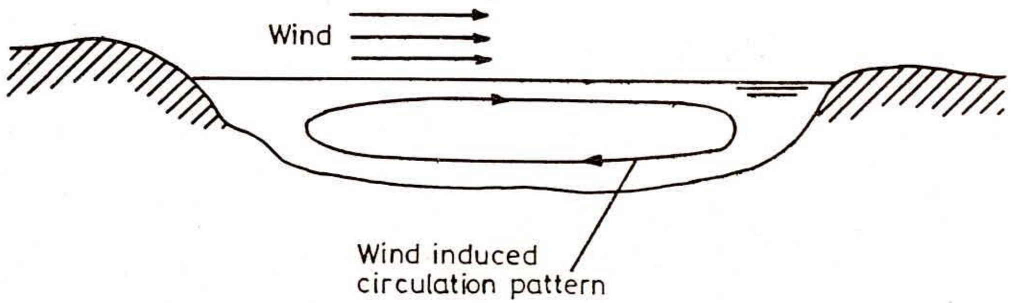


FIG. 2-Circulation resulting from the wind blowing over the surface of a shallow lake
(after Tchobanoglous et al.,1985)

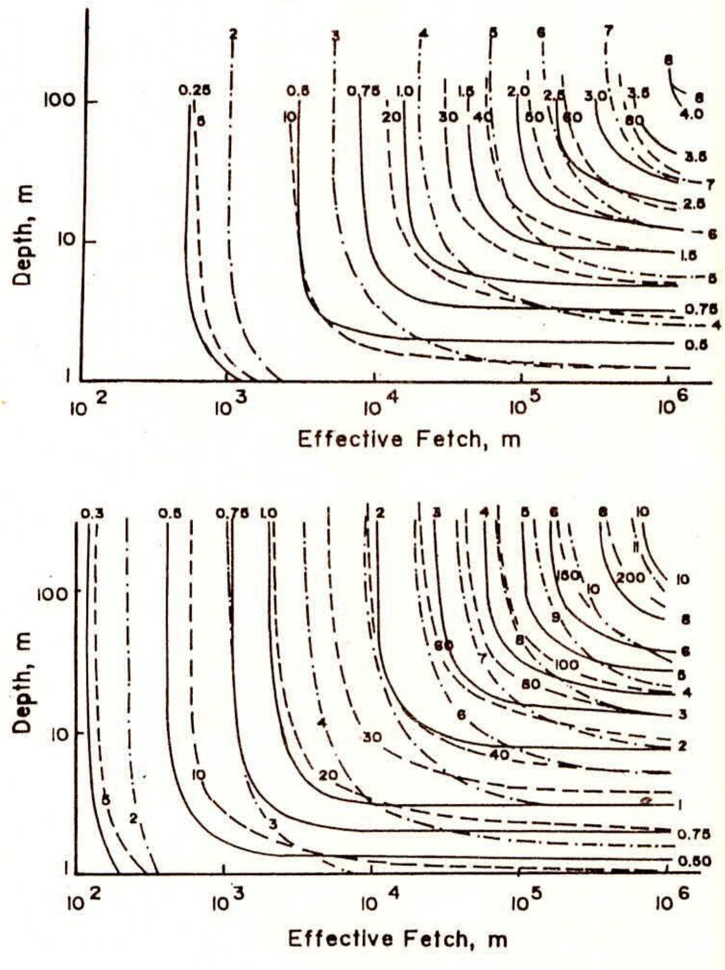


FIG.3:SIZE OF WAVES GENERATED IN BASINS OF DIFFERENT MEAN DEPTHS AND EFFECTIVE FETCHES UNDER 25 KNOT WINDS (TOP) AND 50 KNOT WINDS (BOTTOM) SOLID LINE WAVE HEIGHT (m) DASHED LINE- WAVELENGTH (m) AND DOT DASHED LINE-PERIOD (sec) (AFTER JOHNSON, 1980)

orbital motion of water

$= \pi d_o / T$ ....(4)

d_o = horizontal displacement of the elliptical orbital motion of water

$= H \ / \ \sinh \ (2\pi h/L)$ ....(5)

h = water depth

T = wave period

H = wave height

L = wave length

$= gT^2/2\pi \tanh (2\pi h/L)$ ....(6)

Sediment motion is initiated to first approximation wherever the water depth is less than one half the length of surface waves. Equations 2 to 6 can be applied in these regions to determine the maximum grin size that will be moved. Certain lakes are so shallow that sediments throughout the basin may be stirred up and mobilized by a passing storm. Figure 4 can be used for these lakes. Figure 4, however, can not be used to determine sediment grain sizes moved at various depths in a deep lake as waves migrate into shallower water, because in the large fetch, shallow water region of the graph the wave sizes generated are not as large as waves generated in deep water that migrate into shoal regions.

As waves move into shallower water their periods remain constant and their lengths and heights change according to :

$L/L_\infty = \tanh \ (2\pi h/L)$ which is approximately equal to $[\tanh(2\pi h/L_\infty)]^{1/2}$ ....(7)

and,

$H/H_\infty = (1/2n * L_\infty/L)^{1/2}$ ....(8)

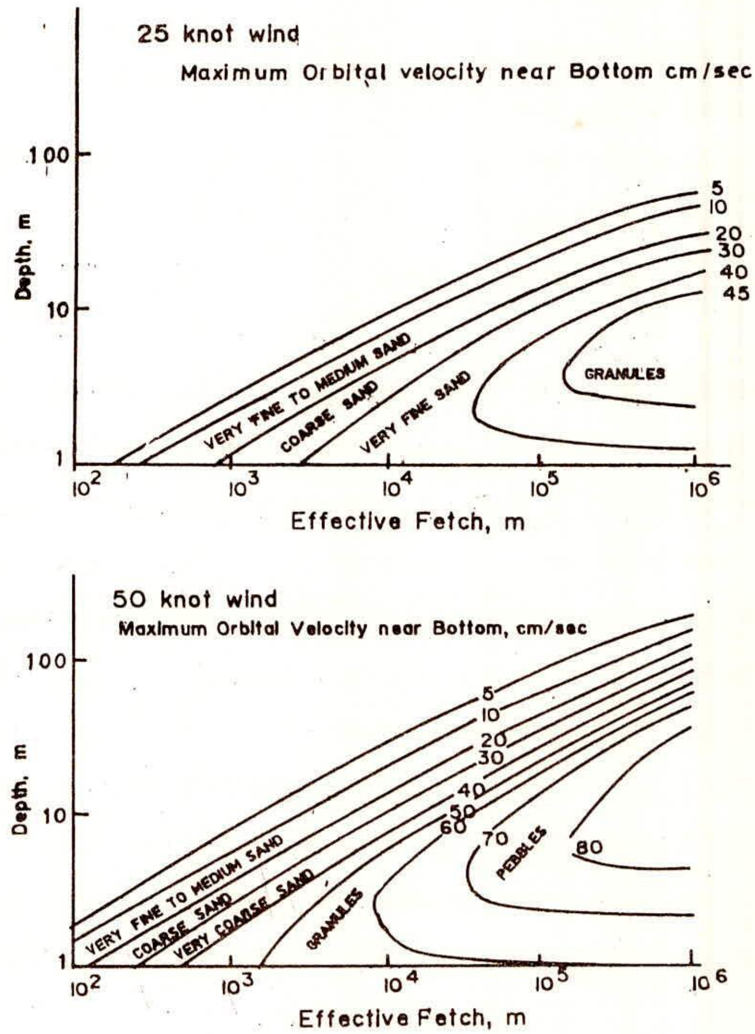


FIG. 4 MAXIMUM ORBITAL VELOCITY AT THE LAKE FLOOR AND THE SEDIMENT SIZE MOVED (AFTER JOHNSON, 1980)

where,

L = shallow water wavelength

H = shallow water wave height

L_∞ = deep water wavelength

L_∞ = deep water height

$n = 1/2 \, [\, 1 + 2kh/\sinh(2kh) \,]$ ....(9)

$k = 2\pi/L_\infty$ ....(10)

By knowing the deep water wavelength and wave height from Figure 3, corresponding wave lengths and wave heights for shallow waters can be found out from equations 7 to 10. These values can then be used in equations 2 to 6 to determine the grain size that can be moved by the wind waves in shallow waters.

UNESCO (1985), has also given theoretical curves for the generation of waves. These are given in Figure 5. These can also be used for finding out the size of the generated waves.

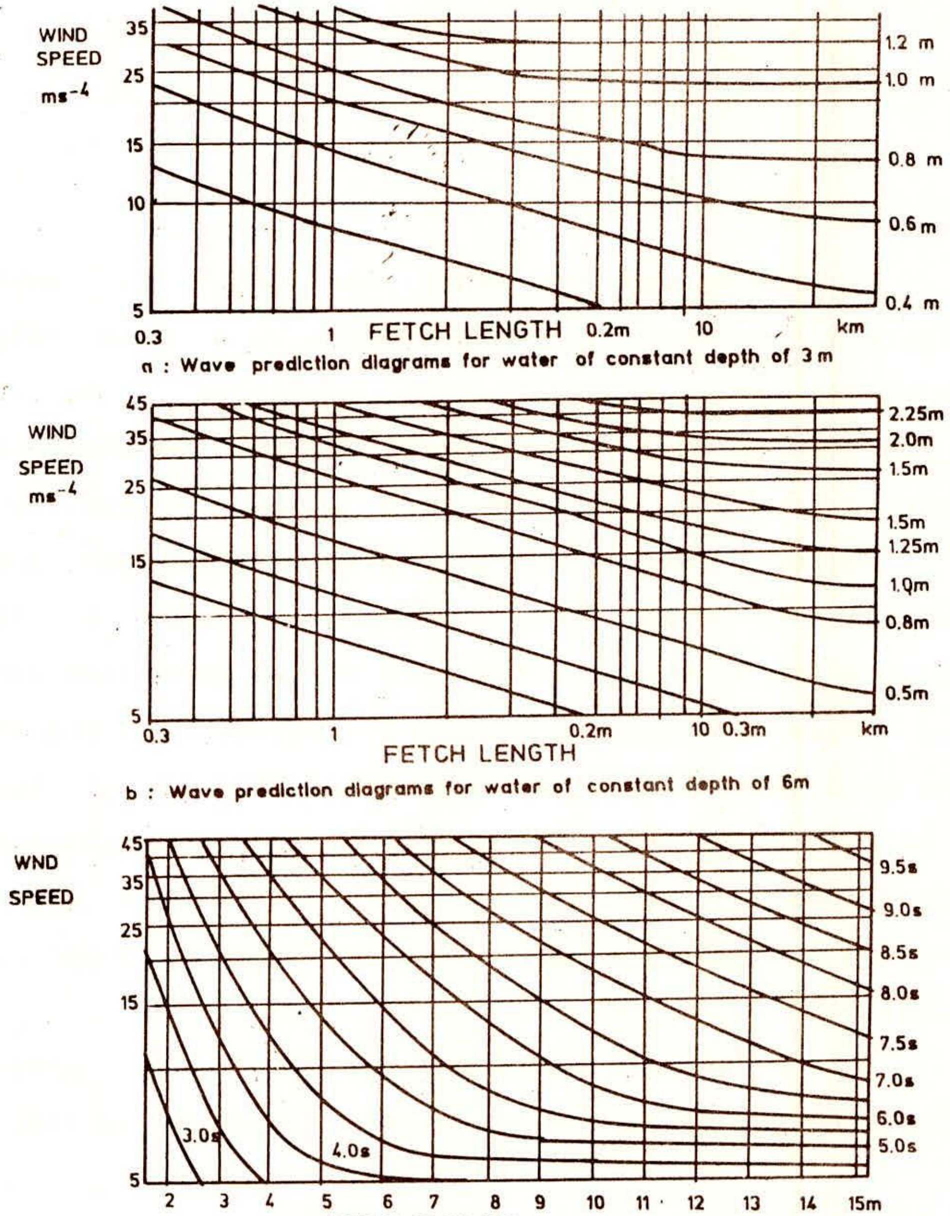
Waves generated by wind are smaller in shallow water than the ones generated in the deep water because of the energy losses to the bottom in friction, percolation and sediment motion. Waves generated in long narrow lake basins are significantly smaller than those generated in more open waters under identical wind conditions (Johnson, 1980).

The following equations are used to predict the significant height, H, and wave period, T (Johnson, 1980) :

$$H = (U^2/g)\, 0.283 \tanh [\, 0.53\, (\, gh/U^2)^{0.75} \,] * \tanh \{\, 0.0125\, (gF/U^2)^{0.42}/\tanh [0.53\, (gh/U^2)^{0.75} \,] \,\}$$

o

........(11)



c :Forecasting curves for significant wave periods

FIG.5 - THEORETICAL CURVES FOR THE GENERATION OF WAVES IN DEEP AND SHALLOW LAKES (AFTER UNESCO, 1985)

$$T = (2\pi U/g)\ 1.2 \tanh\left[0.833\ (gh/U^2)^{0.375}\right] * \tanh\left\{0.077\ (gF/U^2)^{0.25} / \tanh\left[0.833\ (gh/U^2)^{0.375}\right]\right\} \quad \text{........(12)}$$

where,

U = wind speed

g = acceleration due to gravity

h = water depth

F = effective fetch.

Much of the breaker energy of the wind is directed at the shoreline and the erosion of unconsolidated bank material results, with the production of shoreline cliffs. The fine particles are taken into suspension and are carried away from the shore, while the coarser particles remain to form a beach berm and slope system close to the water surface level.

The shear stresses exerted by the wind also induce forward motion of the surficial waters of the basin. The surficial current drift may transport considerable volumes of water along the lake, and at depth counter currents are established returning water to the upwind end of the basin. In shallow lakes the return currents develop near the lake shores. These basin floor currents flow at very much lower speeds than the surface drift. Such currents may be sufficient to carry the concentrated near bed settling suspensions to the windward end of the basin where enhanced deposition may occur.

Lake waters may also respond to wind stress by piling up at one end of the basin in the form of a temporarily inclined water surface. Sudden cessation of the wind releases the water and an oscillation, called seiche, is set up whose period and height depend on the length and depth of the basin. Seiches have little effect on the bottom deposits directly but the turbulence and wave action induced by them causes considerable fluctuations in the water level which in turn influences the inshore - offshore movements of lake sediments, although no measurements are available to indicate the increased rate of sediment transport attributable to such a cause. According to Carter, (1988), observations in the Lough Neagh, Northern Ireland, have shown that during extreme seiches (rarely more than 0.2 m) considerable areas of the inner shore zone are uncovered and recovered. Seiches' effect therefore provides a means for extending the transportive capacity of the water movements under the specific conditions and may account for the presence of some coarser sediment deposits beyond the range of normal depositional conditions (Sly, 1973).

In a stratified lake the relative oscillations of the layers of various densities due to seiches cause considerable flow velocities in the hypolimnion affecting the redistribution of the sediments.

The interaction between waves, currents and sediments in the lake is shown diagrammatically in Figure 6. The influence of waves is modified by the effects of fetch, duration, incidence and bathymetry. Similarly the influence of currents is modified by basin configuration, velocity, direction and density. The sediment response to the imposed shear stress, resulting from wave and current action is itself controlled by additional factors such as particle size, cohesive strength and bed form. The form of sediment response in terms of erosion, transport and deposition therefore represents a final integration of the interaction between external forces and the particulate fraction.

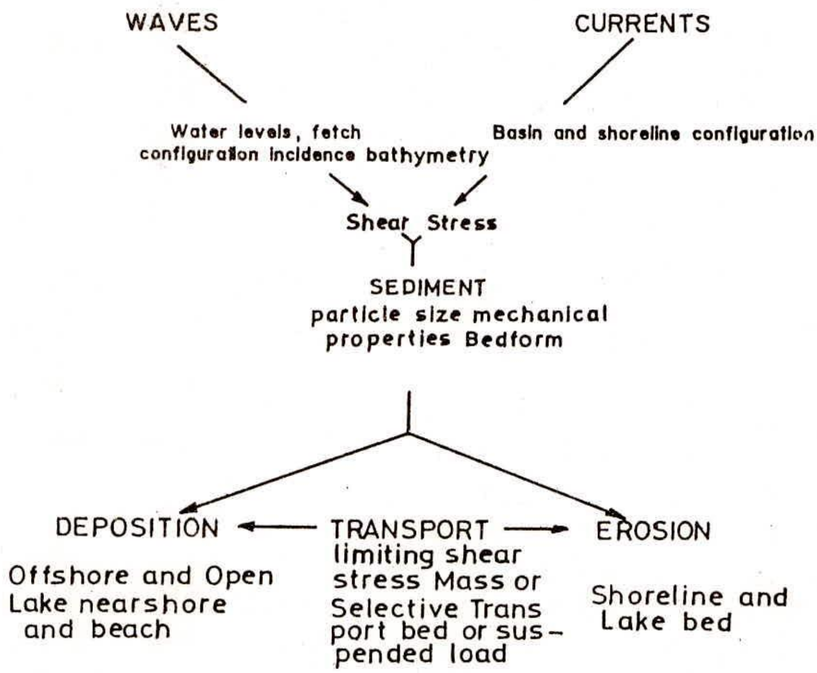


FIG.6-RESPONSE OF LAKE SEDIMENTS TO WAVES AND CURRENTS (AFTER SLY, 1978)

2.5 Role of river inflow

Rivers are said to be the mortal enemies of lakes. All rivers flowing into the lakes carry more or less sediments with them. Suspended sediments travel with the momentum of the river water and, in combination with the dissolved load and with water temperature, their concentration defines the density of the waters entering the lake (UNESCO , 1985). The fine sediments may remain in suspension in the upper waters or are held at the thermocline where substantial concentrations may be held without significantly changing the density of the upper water (Table 4).

The inflowing river do not simply flow straight out into the lakes but are deflected to the right (in the northern hemisphere) as a result of the earth's rotation till the lakeshore presents a barrier and the current is forced along the right shore. The result is general counter clockwise circulation in the lake. Such inflow induced circulations are very common in many lakes (Wright et al., 1980).

Table 4 Variations of density with water temperature and sediment concentration in Lake Brienz and the inflowing Aare River, during floods (after UNESCO, 1985).

Water depth	Temp.	Suspended matter	Density water	Density suspension	Suspension density - water
River	5.4	21400	0.9999842	1.0128435	128593 * 10^{-6}
Lake - Surface	13.8	10.7	0.9992987	0.9993051	64 * 10^{-6}
0.5 m	13.7	4.3	0.9993112	0.9993149	26 * 10^{-6}
10 m	11.0	40.0	0.9996328	0.9996568	240 * 10^{-6}
26 m	8.4	4.8	0.9993509	0.9998538	29 * 10^{-6}
110 m	5.6	54.7	0.9999795	1.0000123	328 * 10^{-6}

Inflowing rivers do not always mix vertically with lake water. The path followed by the sediment laden inflowing river waters is determined by the density regime of the lake. Depending on the relative density of the lake and the river water, the inflowing water may form a discrete layer at the lake surface (overflow), at depth (interflow) or along the lake bottom (Wright et al., 1980). In summer, when the river is stratified, the inflowing warm river waters may be of lower density than the epilimnion, in which case, they flow at the surface of the lake as an overflow. More commonly, the river water density lies between that of the epilimnion and the hypolimnion, in which case, the turbid waters flow along the interface at the thermocline in the form of an interflow. Inflows colder than the lake waters or particularly heavily charged with sediment, have high density and travel into the lake basin along the floor to provide underflows or turbidity currents (Figure 7).

The nature of the transport from the rivers determines the occurrence of turbidity currents or underflows. Where rivers are highly charged with suspensions, as in the first flood of a season, the entering sediment plume plunges down the delta slope towards the basin floor.

Density and in particular turbidity underflows have an important role in sedimentation. Underflows at various times and in various ways are involved in the transport of a substantial portion of the sediment in the lake (Weirich, 1986). While conditions under which underflows occur are of considerable interest, the actual mechanism and movement pattern of these currents are also of concern. In case of the underflows which have high sediment load, variation in sediment carried by the incoming stream, controls the underflow process. Whereas in lower sediment

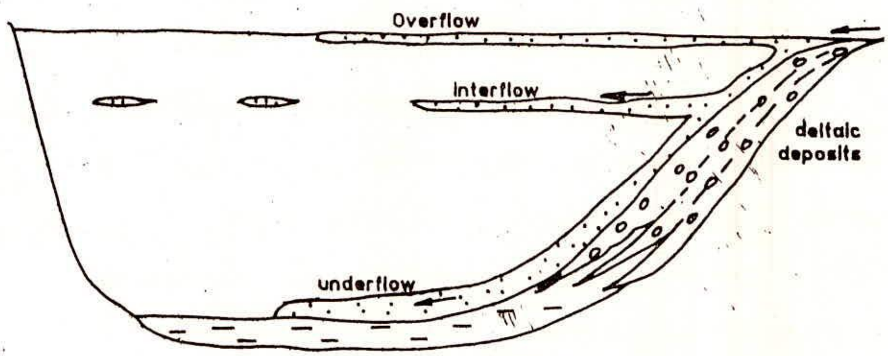


FIG.7 - DISTRIBUTION MECHANISM AND RESULTING SEDIMENT TYPES FOR CLASTIC SEDIMENTATION IN LAKES WITH ANNUAL THERMAL STARTIFICATION (AFTER UNESCO, 1985)

load situations, a complex interplay between thermal and sediment effects occur (Weirich, 1986).

When the river water enters the lake, there is a mixing of the two different water bodies. The mixing of the river water with the lake water causes loss or extraction of CO_2 and evaporation in addition to carbonate precipitation in lakes. G. Muller et al. (1972) investigated highly alkaline Anatolian Lakes of Turkey (pH 9-10) into which enters the river water rich in Ca^- and HCO_3^- ions and a pH of about 7.5. In the mixing zone aragonite precipitates forming whiting due to low solubility of calcium carbonate at elevated pH, reports Fuchtbauer (1974).

The effect of the river input on the sedimentary process may differ substantially depending upon both the rate of discharge and the relative quantities of bed and suspended load. A further influence is the degree to which the river inflow is maintained in entrained phase and to which horizontal and vertical shearing may result in turbulent mixing and subsequent diffusion (Sly, 1978).

2.6 Atmospheric heating and lake sedimentation

The effects of the atmospheric heating may be seen in the thermal and density structure of the lakes. Due to large storage of mass of water and high residence time, lakes have an extremely large capacity to accept heat into storage and subsequently to give it back. This influences the thermal gradient and density of lake water which in turn control the circulation of water.

The effects of density stratification are particularly important with respect to the movement of fine particulates. The path followed by the sediment laden inflowing river water is determined by the density regime of the lake. Solar radiation heats the water in the surface layer and causes thermal expansion of the water. Therefore a decrease in density will be produced so that the surface water is inclined to float upon the denser water below. When stratified, there may be sufficient density difference between the water masses so that very fine particulates are kept in suspension; fines already in suspension may become transported by the hot water during the periods of vertical mixing, overturn and upwelling (Sly, 1978).

In some lake areas the high solids content of inflowing waters (often associated with thermal density effects as well) may produce underflow condition (Sly, 1978).

2.7 Factors controlling movement and deposition of sediments

Apart from the three main natural sources of energy discussed above i.e wind, river inflow and atmospheric heating, characteristics of lake sediments like the grain size, porosity, bulk density and water content, characteristics of the lake water and the morphometric features of the lake basins are the major factors besides few other relatively less significant factors which control the movement and deposition of the lake sediments.

Any particle of a specific gravity greater than that of the water will when placed into water sink to the bottom under the influence of the gravity i.e. will tend to perform downward motion which is counteracted by resistance of water. The drag resistance will depend upon the size, shape and the surface quality of the particle, on density and viscosity of water as well as the fall velocity of the particle. Large particles are settled swiftly whereas silts, clays and finely dispersed low-density organic particles remain in suspension. The fall velocity depends upon the size, shape, specific gravity of the particle and the temperature and viscosity of the water and will be different for different particles (Bogardi, 1974). The fall velocities of the clay particles are generally in a few tens of centimeters per day (UNESCO, 1985).

Grain size provides an important control over transport and deposition of sediments. The size of lacustrine sediment varies greatly; coarsest materials include boulders, pebbles, gravel and sand and the finest material include silt and clay (mud being an undefined mixture of clay and silt). Coarse gravels and sands usually form the bottom deposits in the shallow nearshore environment of lake system. Strong currents or wave action are required to provide the turbulent motion necessary to raise the coarse materials above the bed and because of this they rarely enter suspension.

Because of their smaller particle size, silt and clays remain in suspension longer and move a greater distance out into a lake basin where they can be dispersed by the water movements of large scale circulation. Under some conditions these fine particles may be subject to the effects of seasonal entrained flow and will be transported considerable distances with the large scale circulation of a water body in which both the shape and bottom slope of the basin indirectly influence sediment accumulation (UNESCO, 1983).

Porosity of the lake muds typically range from 70 to 90 % compared to a lower values of generally less than 40 % for sands (Jones et al., 1978). The relatively greater capacity of muds for compaction means that the total advective transport of solutes to the lake by compaction will be greater for muds than for sands.

Most fine sediments are initially deposited along the margins and then move to the deep floors by mass wasting and high concentration flows. Since the fine grained sediments tend to deposit initially on the margins and particularly on the slopes beyond the shelf edge, they are most sensitive to mass failure. Much mud enters the deep floors deposits via fine grained turbidity currents which originate from slope mass failure. Strength of the sediments deposited on slopes is a function of the slope gradient and bulk density, the later being the primary factor. Thus low bulk density sediments can fail on very gentle gradients. The stability of sediments on slope may be low and eventually much of this material moves by gravity processes to the base of the slope. A variety of features may result depending upon the water content and other bulk properties (Gorseline, 1985). Fine unconsolidated bed material with a high water content is re-eroded before the material having a low water content, such as the sub-aerially dried mud of the bank (UNESCO, 1983).

In addition to the characteristics of the sediment, its rate of supply is also important. As the sediment concentration or transport increases, the character of the flow changes. Generally fall velocity and effective fall diameter decreases. The viscosity of the mixture increases. The flow becomes non-Newtonian when the particles interaction becomes dominate. In the turbulent range increased concentration gradients inhibit momentum transport and cause upper layer velocities to increase (McCutcheon et al., 1984). Both character and supply in turn depend upon the source of the sediment and the hydrological processes in operation (Smith et al., 1983).

The characteristics of water which influence the sediments movement are velocity, turbulence, density and viscosity, and salinity. Fine sediment can not settle in an environment in which the level of the turbulence is high, as in the beach environment, unless the rate of the supply is extremely high (Blatt et al., 1972). Density and viscosity of the lake water also affects the movement of the particles. If a particle of density ρ' and diameter d is released in a still liquid of density $\rho < \rho'$ and viscosity μ, it will eventually reach a terminal velocity W_t given by Stoke's law

$$1/6\ \pi\ d^3(\rho'-\rho)q = 3\pi\mu W_t d. \qquad \text{.........(13)}$$

It is also expected that, if the maximum upward vertical velocity of the water in the lake W_{max} is larger than the terminal velocity W_t, some particles will not continuously fall onto the bottom of the lake, but will be carried upward, atleast for a while, before being deposited on the bottom (Giorgini et al., 1980).

The variation in the pH of the lake water influences the downward transport of the organic matter with the sediments (UNESCO, 1983). Deposition of sediments under the influence of chemical flocculation which is related to change in salinity is most important for sedimentation in saline lakes. However, organic matter and calcium may play an important part in flocculation process which can be significant in freshwater lakes also (UNESCO, 1983).

The shape and the depth of lake basins affect the circulation of water within them and therefore has a particular influence on the distribution and deposition of the clay and silt particulates. Smaller the lake the less significant are the effects of the wave action. Increased surface area of a lake, however, permits greater wave action, eroding shores and adding the eroded materials to the bottom sediments. Similarly, subsurface currents operate to a greater extent in large, deep lakes than the small ones. These currents serve to distribute the sediments (Reid and Wood, 1976).

The size of the lake basin largely controls the amount of wave energy by limiting fetch. In long and narrow lake basins wave action is usually directed heavily at the ends of the basin. In broad shallow lakes typical off-shore condition never develop and wave generation is restricted by bed effects (Sly, 1978). In large lakes the wave energies represent a significant portion of the total dynamic energy of the system. In small lakes, however, energy levels may be sufficient only to provide partial and selective transport of incoming sedimentary materials (Sly, 1978).

The size and shape of the lake area influence the distribution of the lake sediments also. Hakanson (1982); report Nuhfer et al. (1985), noted that the percentage of the lake basin area dominated by resuspension and transportation increases with increase in the lake area and decreases with increase in mean depth.

Figure 8 shows the schematic representation of the response of lake to the various forms of physical inputs.

3.0 Estimation of sedimentation

3.1 General

Knowledge of the sedimentation rates in lakes is essential to evaluate the rate at which they are being filled and to understand the cycling of nutrients and trace elements. Lake sediments also preserve and record the processes which have occurred in the overlying water column and in the watershed. The knowledge of sedimentation rate is also necessary to reconstruct

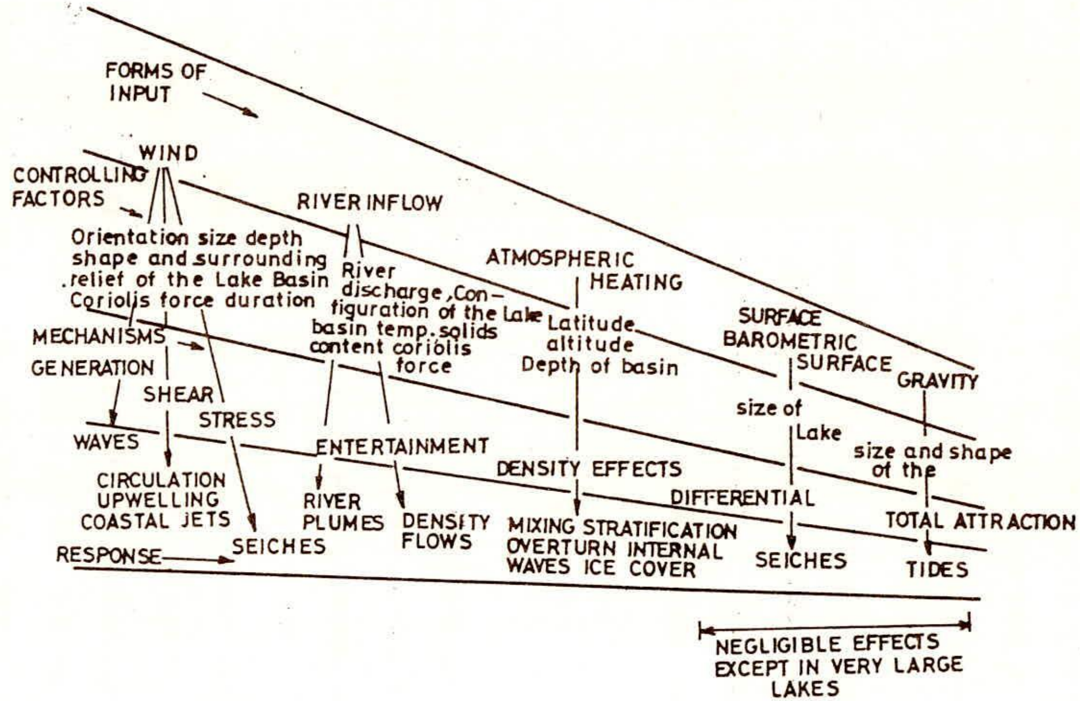


FIG. 8: LAKE RESPONSE TO VARIOUS FORMS OF PHYSICAL INPUT (AFTER SLY, 1978)

the history of processes such as deforestation, climatic changes and pollution.

The surest way of obtaining an accurate determination of the amount of sediment being carried to a lake by streams is to measure the flow rate and sediment concentration of the inflowing waters just upstream of the lake (UNESCO, 1985).

The relation between total sediment transport Q_s and stream flow Q is often represented by a logarithmic plot between water discharge (abscissa) and suspended sediment discharge (ordinate) which may be expressed mathematically by an equation of the form,

$$Q_s = kQ^n \qquad ....(14)$$

where n commonly varies between 2 and 3, and k, the intercept when Q is unity,is usually quite small (Linsley et al, 1964).

Sediment is usually divided into fine sediment (particle size less than 0.062 mm) and coarse sediment (particle size greater than 0.062 mm). However, for the purpose of measurement lake sediments are broadly grouped into two categories i.e. suspended load and bedload. The part of the coarse sediment, the smaller particles, which tends to be carried in suspension alongwith the fine sediment is called the suspended laod. Other particles, especially the larger ones move by rolling, sliding, or hopping in almost continuous contact with the bed. This material composes the bedload.

3.2 Methods of estimation

Various methods are used to estimate the total sediment load and rate of sediment accumulation in lakes. These are discussed in this section.

3.2.1 Sampling

3.2.1.1 Suspended sediment measurement

Measurements of suspended sediment concentrations using sediment samplers involve collecting a sample of the water-sediment mixture, separating the sediment, and weighing. However it should be remembered that the concentration of suspended sediment changes from point to point in the cross-section and fluctuates in time at a fixed point. The kind of sampler and the technique of sampling, therefore, should be selected according to circumstances and to the desired accuracy of the measurement. If the sediment is separated by evaporation, a correction has to be made for dissolved solids.

The suspended sediment samplers can be either instantaneous type or time-integrating type. The instantaneous samplers are usually trapping devices consisting of a horizontal cylinder equipped with end valves (Fig. 9) which can be closed suddenly to trap a sample of water-sediment mixture passing the selected sampling point at a given point in time. The time-integrating sampler takes a sample more slowly over an extended period of time to obtain a concentration averaging the instantaneous or occasional fluctuations of suspended sediment transport over the sampling period of time. The time-integrating samplers may be either point-integrating or depth integrating samplers. The point-integrating sampler (Fig. 10) is held stationary at the point in the sampling vertical during the sampling period of time, and them moved, with the sampling action stopped, to a second point, and so on. The depth-integrating sampler (Fig. 11) is lowered to the bottom of the stream or lake and raised again to the surface at a uniform rate, sampling continuously during both periods of transit. Sometimes it is

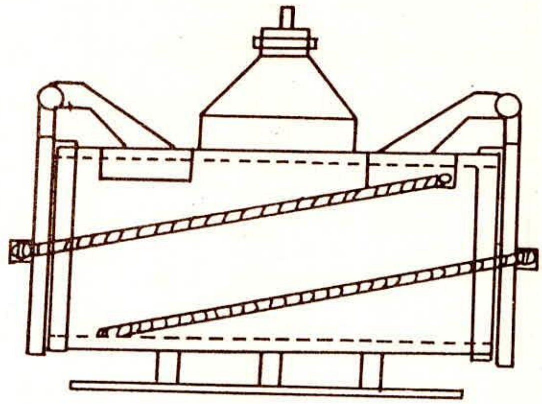


FIG.9- INSTANTANEOUS SAMPLER

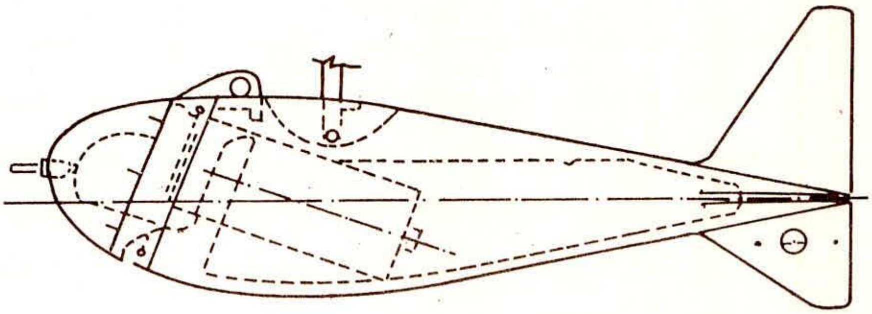


FIG. 10- U.S.A. SERIES POINT INTEGRATING SAMPLER

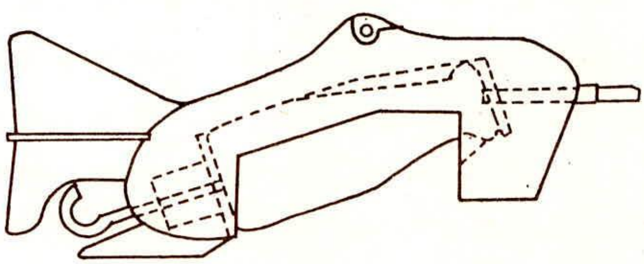


FIG. 11- U.S.A. SERI[illegible] DEPTH INTEGRATING SAMPLER

lowered only for sampling continuously from the surface to the bed, so that mean concentration from the vertical is obtained. Point-integration samplers are more versatile than the simpler depth-integrating types. However, for every size of point-integrating sampler there is a limiting depth below which the sampler should not be used (WMO, 1981).

The average suspended sediment concentration at a vertical in a crcss-section can be determined either by averaging the concentrations measured at different points along the vertical, or by using a depth-integrating sampler which automatically takes a sample in which the concentration of suspended sediment equals the average concentration in the vertical.

About 65 different types of samplers are presently being used all over the world (WMO, 1981). However most of them are useful for sampling of rivers and streams with high velocities. In lakes, however, the flow velocities are very low and hence the disturbance to flow is negligible so the use of vertical samplers is advocated. The vertical cylinder or pipe forming the container is lowered to the desired depth and an instantaneous or time integrated sampler is collected by operating the valves at either end of the instrument. The latter is suitable for taking samples very close to the bed (WMO, 1981).

3.2.1.2 Accuracy in measurement of suspended sediment

As already stated the concentration of fine sediment in the water depends on the amount supplied by the drainage basin and is usually associated with rainfall. The concentration depends only indirectly on the flow rate or carrying capacity of the stream. Since the concentration of fine sediment can be highly variable with time (variations by a factor of 100 to 1000 are common) much of the error in sampling results from the lack of enough observations to define the large temporal variations.

For accuracy the proper selection of verticals is more important than the method of sampling. WMO (1981) has given a nomograph for determining the required number of sampling verticals for streams. However, the validity of the nomograph for lakes has not been specified.

3.2.1.3 Bed load measurement

Measurement of bed load discharge is extremely difficult. Stevens estimated bed load as 15 percent of the suspended load (Linsley et al., 1964). Einstein has presented an equation for the calculation of bed load movement on the basis of the size distribution of the bed load material and streamflow rates, report Linsley et al.(1964).

Usually the measurements are made with samplers. Unfortunately, the amount of material transported as bedload is extremely sensitive to the local water velocity and no physical sampler can be placed in the flow without disturbing the water velocity near the sampler (UNESCO, 1985).

The basket-or box-type sampler (Fig. 12) is probably the most commonly used sampler for bed load determinations. It is made of wire mesh material mounted on a rigid steel frame. The mesh has openings of a size that passes the suspended sediment but retains bed load. The upstream end of the basket is completely open and thus able to catch the largest cabbles. Bed -load discharge is determined from the amount of sediment trapped per unit time in the sampler.

Measurements should be performed at various flows so

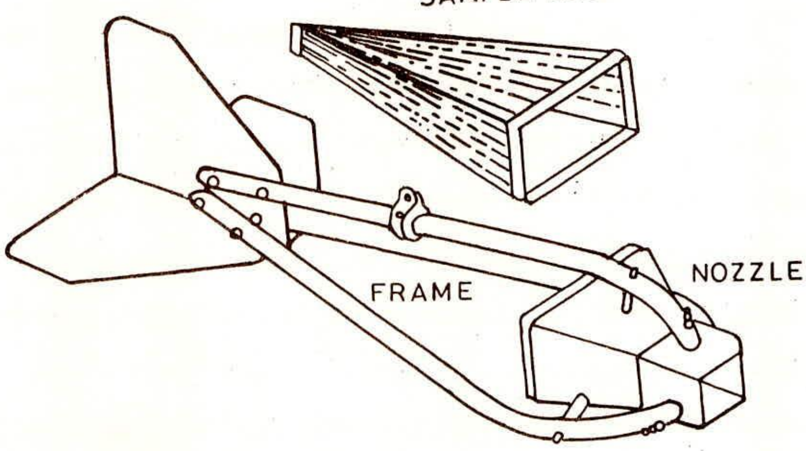


FIG. 12. BASKET - TYPE BED-LOAD SAMPLER

that a rating may be prepared showing the relation between stream discharge and bed-load discharge. Due to the highly complex and random nature of sediment movement, and to the errors of sampling, a single catch at a measuring point provides only a very uncertain estimate of the true bed-load transport. Therefore, repeated sampling should be carried out at each point.

Bed-load traps are sometimes used for the estimation of bed load. These are slots, trenches, or small pits built across the stream channel to catch sediment moving in contact with the bed. The amount of sediment caught in the trap is collected and weighed. Bed-load traps provide the most direct method for sediment measuring and that their efficiency is virtually 100 percent. However, their high cost and difficult installation prevent their general use. In addition, the frequently repeated pumping or digging of trapped sediment and the maintenance of the apparatus is rather expensive.

Tracer techniques are also used for estimating bedload.

3.3 Surveying method

This method is used to find out the rate of deposition of sediments in a lake over the years. Bathymetric maps of the lake are prepared for different years. The rate of sediment accumulation is computed from the difference in the volume of the sediment deposited by comparing the maps of different years (Ghosh, 1992).

There are two methods of surveying, range-line method and contour method. In the range-line method number of cross sections of the lake are surveyed and then periodically resurveyed with the help of echo sounders. These cross sections are called ranges. This method usually requires less field work and is less expensive than the contour method. The accuracy depends on the number of range lines, the accuracy of application of echo sounding and the spatial variation of the sediment deposits. In loose deposits the sounding rod gives uncertain depth data (WMO, 1981).

The contour method uses essentially topographic mapping procedures. This method is generally used when higher degree of accuracy is needed. Like the range-line method, this method also involves the determination of bed elevation. Echo sounding is used for this purpose (UNESCO, 1985). The main disadvantage of this method is that it is limited to times when the lake is empty or has only shallow water cover (WMO, 1981). To apply this method it is important to have a good contour map of the lake before filling. Selection of the contour interval is controlled by the same factors which are used in selecting a map contour interval, but it is suggested that interval should not exceed 1.5 m and 0.5 m for large and small lakes respectively (Ghosh, 1992).

3.4 Remote sensing technique

Remote sensing methods can be effectively used to assess sedimentation in lakes and reservoirs as it can provide timely and repeated information concerning suspended sediment flow pattern in lakes. Remote sensing sensors operating in visible region of EMR record the reflected component from the terrain feature and convert the reflected radiation to electrical signals. These analog signals are sampled on board platform and are converted to digital numbers (DNs) which are transmitted to receiving station. These DNs have linear relationship with the reflected radiation (Jain, 1993). As turbid water is more reflective than the clear water and as it is related to suspended sediments remote sensing technique uses turbidity as the measure of sedimentation.

Satellites provide landsurface imageries at regular intervals from which spread area of sediments can be identified. However, the remote sensing techniques can not quantify the total sedimentation in a lake. Moreover, remotely sensed data represents only the near surface conditions.

3.5 Isotope techniques

Lake sediments contain valuable information regarding the recent history of environment of the drainage basin. Dating of the lake sediments thus can be used to estimate the sedimentation rates.

Dating organic sediments by the ^{14}C method has been used to give sedimentation rates over the last one to fifty millennia but does not extend to the present time. However, recent advances in measuring environmental radionuclides have given two promising methods for determining sedimentation rates over the past 150 years: the ^{137}Cs method from the present to 1954 and the ^{210}Pb method from the present to 150 years ago (Schell et al., 1983). A discussion of ^{137}Cs is presented here. For ^{210}Pb method description Payne (1985) and Schell et al.,(1983) can be referred.

^{137}Cs is absorbed on the micaceous components of the sediments in fresh water lakes. During the accumulation of sediment, each layer will have a ^{137}Cs content determined by the deposition of ^{137}Cs at the time of formation of that layer. The ^{137}Cs profile in the sediment, showing variation in its deposition in lake sediments, is obtained from core samples. The cores are cut into 0.5, 1.0 or 2.0 cm sections and measured (Payne, 1985). A profile of ^{137}Cs concentration against depth (Fig. 13) shows a

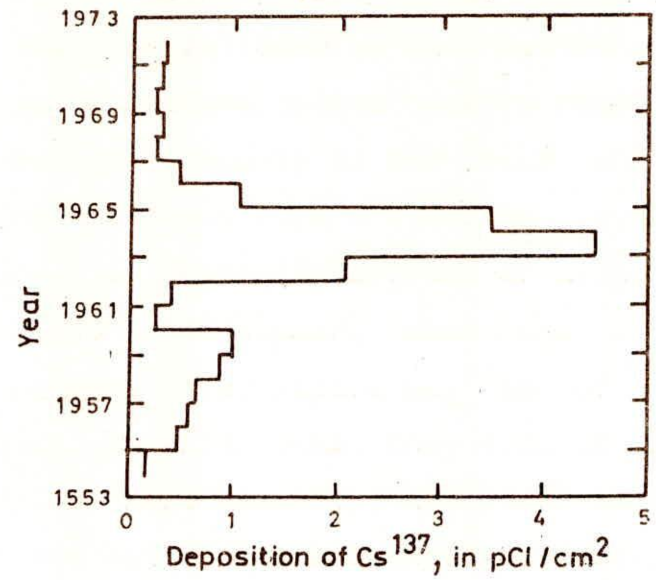


FIG.13·1–AN EXAMPLE OF THE ANNUAL DEPOSITION OF ^{137}Cs

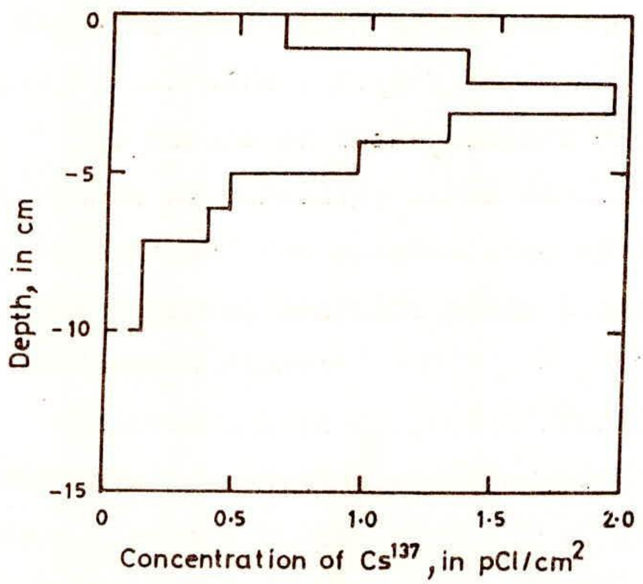


FIG.13·2–A HYPOTHETICAL DISTRIBUTION OF ^{137}Cs IN LAKE SEDIMENTS maximum activity at a depth which corresponds to 1963 and the depth where ^{137}Cs is first detected which corresponds to 1954. The sedimentation rate is estimated for the period 1963 to present (R_1) and also for the period 1954 to present (R_2) as,

$$R_1 = \frac{D_{max}}{(Y-1963)} \quad ......(15)$$

$$R_2 = \frac{D_o}{(Y-1954)} \quad ......(16)$$

Where,

D_{max} = depth of maximum ^{137}Cs concentration corresponding to 1963

D_o = depth of first appearance of ^{137}Cs in core corresponding to 1954

Y = year of sampling

4.0 Sedimentation and lake water quality

Sediments are eroded, transported and selectively sorted into deposits. They have different textural properties which are caused by various combinations of wave action, current motion and water density separation. While, therefore, sediments may be considered as integrators of many environmental processes, the characteristics of different depositional sites can be considered largely unique (UNESCO, 1983).

The character of the sediments controls the chemical composition of the lake water. So, the interaction of sediments with the lake water, both within the water column and at the bed of the lakes, controls the quality of surface water.

Water quality in lakes is related to eutrophication (Tchobanoglous et al., 1985). Lakes generally begin as oligotrophic water bodies having low nutrient levels. With passage of time, sediments accumulate in lakes. Sediments may provide a means of transport and/or sink for both nutrient and toxic contaminants by means of chemical processes such as adsorption, ion exchange, co-precipitation or chelation. Not all reactions are possible however in all sediments. Several of these reactions are pH dependent and since pH condition changes, sediments may release the contaminants and thus act as a source of nutrients and toxic contaminants (UNESCO, 1983).

The water quality degradation from eutrophic processes is primarily caused by an overgrowth of aquatic plants. The nutrients carried into the lake waters by the sediments increase the productivity level of the lake which is responsible for the excess phytoplankton growth. Excess plant growth causes severe diel fluctuations of oxygen, often large fluctuations in alkalinity and pH, and a loss of water clarity (Waite, 1984).

Eutrophication causes an increase in the zooplankton also. When the organisms die, their remains, along with organic debris from the area surrounding the lake, settle to the bottom into the hypolimnion. Initially there is a considerable erosion of glacial till into the lake that rapidly buries the sedimenting organic matter and prevents return of its nutrients to the lake water. Later, after this first phase, a rather steady supply of nutrients from soil and organic remains is carried into the lake, supporting a rather constant biological productivity over the year (Berner et al, 1987).

Sediments brings minerals to the lake. Minerals such as nitrogen and phosphorous help in accelerating the plant growth.

When the sedimentary minerals are deposited in the lake they are subjected to the changed physical and chemical environment due either to the decomposition of the buried organic matter and/or physical or chemical mixing caused by bottom organisms. These changed environments bring change in the mineralogy and chemistry of the added sediments giving rise to new types of sedimentary minerals. The mineralogy of the lake sediments depends upon the physiographic environments within the lake and its immediate surrounding area. Runoff from terrain of high relief may supply coarse material with abundant and sometimes mineralogically complex lithic fragments. (Jones et al., 1978).

The nature of the sediments depend on the rock type in the drainage area of the lake which in turn determines to a large extent the inorganic mineral composition of the lake water. Thus lake water draining from a limestone area is very much like that given in equation 17 and lake water in a crystalline area is very much like that given in equations 18 & 19 below, because the chemical composition is regulated by the reactions given in these equations (Stumm & Baccini, 1978).

$$\underset{\text{calcite}}{CaCO_3} + CO_2 + H_2O = Ca^{2+} + 2HCO_3^- \qquad ....(17)$$

$$\underset{\text{Na-feldspar}}{NaAlSiO_8(s)} + CO_2 + 5\tfrac{1}{2}\,H_2O = Na^+ + HCO_3^- + 2H_4SiO_5 + \tfrac{1}{2}\,\underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4(s)} \qquad ....(18)$$

$$\underset{\text{montmorillonite}}{3Ca_{0.33}Al_{4.67}Si_{7.33}(OH)_4(s)} + 2CO_2 + 2H_2O = Ca^{2+} + 2HCO_3^- + 8H_4SiO_4 + 7Al_2Si_2O_5(OH)_4(s) \qquad ....(19)$$

Mechanisms and rates of transfer of solutes between lake water and sediment are functions of mineral surface area which in turn are closely related to grain size. Fine grained materials have the most potential for interaction with the lake water (Jones et al., 1978). Amorphous and crystalline ferric oxides, most commonly occurring as surface coatings on grains, are able to exert chemical activity which is far out of proportion to their mass concentration (Jones et al, 1978).

All clays have significant cation exchange capacity (C.E.C.) through which they can bond and transport several compounds including many pollutants. Cation exchange capacities of some of the clay minerals are listed in Table 5. Clays also adsorb large quantities of phosphate. Golterman, (1975), has cited values of adsorbed phosphate (per 100 gm) on kaolinite of 31.2 meq. at pH = 7.2 and 88.2 meq. at pH = 8.2.

Table 5 Cation exchange capacities of some clay minerals (after Jones et al, 1978)

Clay mineral	C. E. C. (meq/100 g)
Kaolinite	3 - 15
Illite	10 - 40
Chlorite	10 - 40
Smectite	80 - 150
Vermiculite	100 - 150

Mineralogic differences in clays plays an important role in regulating solute transfer to lake waters because of the variations in surface area for different minerals of equivalent grain size and the significant differences in ion-exchange and sorptive capacity of various clay mineral species encountered in lakes.

The fine particles and the detritus in the lake, scavenge chemicals from the waters on to the particle surfaces which, in some cases, leads to enrichment of the sediment in potentially toxic substances so that the entrainment of bottom sediments during the overturn period can be detrimental to the condition of the waters (UNESCO, 1985).

The density effects which are related to sediments play an important role in the water qulity of lakes. The density stratification affects the dissolved oxygen system. Dissolved oxygen is mobilized in lakes by the biological activities of the phytoplankton along with the atmospheric diffusion. Dissolved oxygen levels typically remain high in the surface water because of the availability of light and nutrients that support the algal growth. High flux of suspended load, however, can reduce the availibility of light by increasing the turbidity level. In the hypolimnion the dissolved oxygen level are generally low due to rapid rate of uptake because of biological and abiotic processses (Waite, 1987). The degree of horizontal and vertical stratification of the lake may have a significant effect on water quality by trapping chemicals in regions of reduced exchange and water interaction. Thus the extent of thermal stratifiction also influences the vertical dissolved oxygen profile where reduced dissolved oxygen often occurs in the lower layer due to minimal exchange with aerated water in the top layer (Thomann et al., 1987). The turnover, caused by differences in the densities of the epilimnetic and hypolimnetic waters, affects the water quality in two ways (Tchobanoglous et., 1985) : (1) by changes in nutrient and temperature distribution and (2) by movement of bottom material throughout the volume. Sediments are mostly deposited at the bottom. When these materials are brought to the surface with sunlight and higher temperature and oxygen concentrations, eutrophicatin rates are increased.

With respect to water quality, microbial processes in sediments are often as important as those in the overlying water. Sediment is a substrate for a bacterial activity. The type of bacteria found in sediments depends to a large extent on the type of substrate. Bacterial activity using orgnic substrates is intimately ralated to the oxygen balance of the system as wll as the loss of organic material. The oxygen take up by sediments, as a result of chemical and bacteriological decomposition, can be measured by using the following formula (Golterman, 1975) :

$$Y = X^{0.485} \qquad \ldots\ldots\ldots(20)$$

where,

Y = oxygen demand, mg/litre

X = sludge depth, cm.

In addition, inorganic transformations can be performed by bacterial activity in sediment, for example, nitrification.

The organic matter in the sediments which compose of the phytoplankton cells and macrophytes together with the detrituts derived from the decaying material influences the water quality; (1) by supplying energy or organic carbon, for example for bacteria or blue green algae, (2) supplying accesory growth factors for example vitamins, (3) by having toxic effects and (4) by adsorbing light and thereby affecting photosynthesis (Golterman, 1975).

Thus sediments have a profound effect on controlling the quality of the lake water.

Tables 6, 7 and 8 yield some useful data regarding the quality of some of the Indian lakes.

Table 6 Average of some selected chemical parameters at different stations of Lake Mir Alam, Hyderabad
(after Satya Mohan, 1991)

parameter	Main basin (mg/l)	Near shore (mg/l)
Carbonates	48.3	27.2
Biacarbonates	265.2	305.3
Chlorides	50.8	49.9
Dissolved oxygen	6.7	4.6
Dissolved organic matter	5.7	5.3
Nitrites	0.003	0.015
Nitrates	0.60	0.66
Total silicates	17.88	19.36
Total iron	0.121	0.310
Dissolved solids	551.68	647.05
Suspended solids	119.56	125.40

Table 7 Chemical feature of Renuka Lake

(after Singh et al., 1987)

Parameters (mean values)	Stagnant period Surface	Stagnant period Bottom	Overturn period Surface	Overturn period Bottom
Dissolved oxygen(ppm)	8.0	0.0	4.3	1.5
Free CO_2 (ppm)	0.0	9.2	7.4	15.2
Chloride(ppm)	30.6	40.0	35.0	40.0
Silicates(ppm)	18.0	36.0	31.0	42.0
NO_2-nitrogen ($\mu g/l$)	traces	5.0	8.0	12.0
NO_3-nitrogen ($\mu g/l$)	75.0	120.0	185.0	255.0
NH_3-nitrogen ($\mu g/l$)	35.0	82.0	72.0	94.0
Total PO_4 ($\mu g/l$)	222.0	365.0	395.0	412.0

Table 8 Chemical composition of offshore and inshore areas of Dal lake (after Zutshi, 1987)

Parameter	Inshore		Offshore	
	1969	1980-82	1969	1980-82
Ca (mg/l)	34	42.4	17	29.6
Mg (mg/l)	10	16.5	5	16.2
PO -P (µg/l)	20	92.6	trace	11.3
NO -N (µg/l)	111	556.0	25	62.0

5.0 Conclusions

1. Sedimentation starts to destruct the lake from the very moment it comes to existance through erosion and deposition of sediments.

2 The major effects of sedimentataton, affecting its utility, are reduction in storage capacity and deterioration of water quality.

3. Wind is the most dominating factors in the process of lake sedimentation through its direct effect of bringing sediments in the lake and indirect effect of determining the circulation patterns of the lake. The other chief natural agencies are river input and atmospheric heating. Besides, there are various other factors like lake morphometry, charactristics of the sediment and lake water etc. which control the process of sedimentation.

4. The sedimentary processes of saline lakes are different than the freshwater lakes because of environmental and morphological differences of the two settings.

5. Various methods being used for the estimation of sedimentation include sampling, surveying, remote sensing, nuclear techniques. Out of these, sampling is the most common. Although a

large number of samplers are in use all over the world most of them are unsuitable for lakes because of the differences in flow characteristics of lakes and other streams.

6. Remote sensing can provede timely and repeated information about sedimentation but presently it gives only a qualitative informatin and not quantitative; that too about the surface water conditions only.

7. Radioactive isotopes can be effectively used to determine the rate of sediment accumulation over the years.

8. Lake sedimentation affects the water quality through the bio-chemical activities of the sediments. Water quality is related to eutrophicaton which in turn depends upon the supply of nutrients through the sediments.

9. Lake sedimentation studies are of utmost importance from lake management point of view. It helps in linking the various factors affecting the process of sedimentation and hence the life of the lake.

10. In India the status of research on physical aspects of lake sedimntation studies is very poor and attention needs to be paid without delay to conserve these valuable natural resources from undergoing untimely destruction. The life of many lakes is already reported to be in peril.

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