ISOTOPES IN LAKE MANAGEMENT: A CASE STUDY OF LAKE NAINITAL, UTTARAKHAND

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ISOTOPES IN LAKE MANAGEMENT– A CASE STUDY OF LAKE NAINITAL, KUMUAUN HIMALAYAS, UTTARAKHAND

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INTRODUCTION

Knowledge on hydrology of lakes is essential for their proper use and conservation. Lakes provide water for domestic and industrial uses, fisheries, transport and recreation. Lakes contain over 95% of the earth's surface fresh liquid water. Four types of applications, most frequently undertaken, using isotopes for the studies of lakes are; i) Lake dynamics investigations (i.e., hydrodynamics and/or concentration dynamics of solutes, in terms of transport and mixing rates in both horizontal and vertical directions) and related water balance computations, including evaporation and groundwater inflow and outflow rates, ii) Sedimentation rate and pattern, iii) Gas exchange between lake water and the atmosphere and iv) Palaeo-hydrologic and palaeo-climatological problems, etc.

In this lecture, hydrological studies of Nainital using isotopes are discussed in detail.

NAINITAL LAKE, UTTARAKHAND STATE (Northern India)

Nainital Lake, located in the Kumaun Lesser Himalaya is the main drinking water source to the people living in and around the lake basin. Isotopic investigations have been carried out in order to understand the hydrodynamics of the lake (surface water and groundwater interaction, water balance etc) and to throw some light on the present sedimentation status to estimate the expected useful life of the lake. Additional investigations were also taken up to understand the pollution status of the lake as the investigations were aimed to aid the Lake Development Authority in adopting appropriate management strategy.

The isotope techniques for lake water balance studies are theoretically sound but there are very few successful applications that have been reported. This is mainly due to lack of co-ordinated approach for a clear understanding of the hydrological regime by using both conventional and isotope techniques to substantiate facts rather than to be complementary. A few lake studies in Europe and North America have been carried out using the isotopic technique with the focus on lake-groundwater interaction (Dincer, 1968; Fontes et al., 1970; Krabbenhoft et al., 1990; LaBaugh et al., 1997). However, these are mostly low to mid altitude lakes assuming hydrological and isotopic steady state conditions. In the Himalaya, no lake-groundwater system has been studied so far using conventional techniques, let alone stable isotope technique.

Increase in population pressure has resulted in the deterioration of the environment of Lake Nainital. The conventional methods, either using discharge-sediment concentration or periodic bathymetric surveys usually provide adequate information required for computation of lake sedimentation rates. Lake sounding data, annually collected by Uttar Pradesh Public Works Department, Nainital Division (UPPWD) is the only periodic information available on the lake morphometry. The soundings are made without any proper positioning system along 10 different sections (Fig. 1). This sounding data has been used to estimate the sediment accumulation rate and the lake life by earlier workers (Hukku et al., 1968; Sharma, 1981; Rawat, 1987). As part of the present attempt to estimate the sedimentation rates and lake life, a complete set of data, for the period from 1950 to1995, was analysed. This revealed some serious shortcomings in the bathymetric data. Hukku et al. (1968) while analysing the lake sounding data pointed out some anomalies in the data, and used only a part of the data to estimate lake life. Two other earlier investigators (Sharma, 1981; Rawat, 1987) also adopted a similar strategy and used only that part of the data, which indicated sediment accumulation. Therefore, keeping in view the importance of the lake, an effort has been made for the first time to estimate the life of the Lake Nainital by determining the rate and pattern of sedimentation using ^{137}Cs and ^{210}Pb dating techniques and sediment balance approach.

The term hydrodynamics in lake studies includes the processes such as turbulence characteristics of horizontal currents, thermal regime, vertical exchange and eddy diffusion in case of vertically stratified lakes and water retention time. The need for the knowledge of hydraulics of lakes arises when one is interested to know the fate of pollutants or any unwanted material introduced into the lake. The thermal regime of a lake is of great significance, as temperature influences the chemical & biochemical reaction rates. It also acts as a tracer of mass transport in the water column, so that heat balance may be considered as a primary tool for estimating vertical mixing rates. The thermal regime of lakes is basically a result of heat & momentum transfer across the surface of the lake and also due to the force of gravity acting on density differences with in the lake. In general the heat transfer at the surface tends to raise the temperature during summer and lower during winter. Therefore, the temperature difference at the top and bottom gives rise the mixing currents, but in summers these currents make a small depth cycle while during winter when the top layers become cooler in comparison to deeper, the sinking process starts which has greater mixing effects. Thus, a lake of medium depth undergoes a complete mixing process and remains well mixed during winters while stratified during summers. This phenomenon is a consequence of several meteorological & other factors. The mixing and stratification behavior of Nainital lake has been studied with the aid of isotopes also and is discussed in this paper.

STUDY AREA

Lake Nainital (29° 23' 09" N and 79° 27' 35" E) is a high altitude (1937 m above m.s.l.) natural lake (Figure 1) located in the Nainital District, Uttaranchal, India. It is a crescent-shaped lake with a maximum length of 1.4 km and width of 0.45 km. The maximum and mean depths of the lake are 27.3 m and 18.5 m respectively. The surface area of the lake is 0.46 km^2 with a maximum capacity of 8.57 Mm^3. The lake is bound in the east by the Sher-ka-Danda hill; the landslide deposit called Flat in the north; Ayarpatta hill in the west and Balia ravine in the south. The altitudes of higher peaks surrounding the lake are Naina peak - 2610m, Snow view peak- 2230m, Deopatta peak- 2434m, Ayarpatta peak- 2329m, and Sher-ka-danda peak- 2110m. The mean hill slope of the catchment is 19°, varying between 5° and 49° (Rawat, 1987). The total population in the basin is around 40,000. The lake is a major summer resort in north India, and attracts nearly 100,000 tourists annually. Tourism is the major industry of this region and there is no major agricultural or industrial activity within the study area.

The Nainital catchment is characterized by monsoon type climate. The monsoon period in the study area is generally from mid-June to mid-September. The monsoon precipitation is moderate to heavy and mainly due to moist air-currents from the Bay of Bengal. During winter season (January to March), the precipitation is generally light to moderate with occasional snowfall. The mean annual rainfall of the basin is 2488 mm. The rainfall received during the monsoon season plays an important role in the hydrology of Nainital area as it accounts for about 86% of the total annual rainfall. Monthly rainfall data of three stations viz. Manora, ATI and Snowview indicate that there is no significant spatial variation in the precipitation. Domestic water supply to the Nainital town is met through pumping of groundwater from deep tube-wells and an open-well located at the northern bank of Nainital lake and from few natural springs.

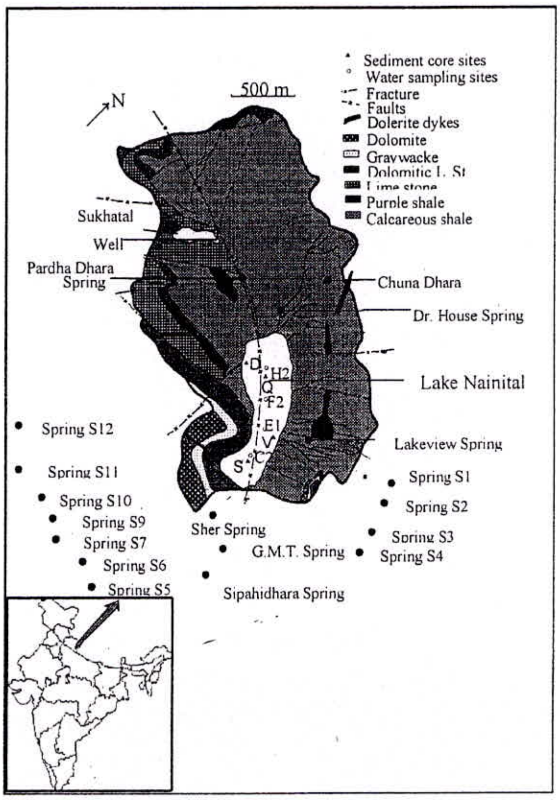

Figure 1. Index map of the study area showing the Nainital lake, locations of springs and geological features.

LAKE WATER BALANCE

Lake water balance approach physically accounts for the components of outflow and inflow to the system and the change in storage within the system over a period of time. The water balance method is normally used to estimate the net groundwater inflow (groundwater inflow - groundwater outflow) to the lake, provided the other water balance components are known. The water balance equation for a lake is written as,

ΔV = inflow - outflow

Where, ΔV is the change in lake storage for a selected period of time. Incorporating different inflow and outflow components and rearranging, the equation becomes:

$$SS_I - SS_O = (E_O + S_O - \Delta V) - (P_I + S_I + D_I) \qquad ......(1)$$

where,

SS_I = sub-surface inflow to the lake [L^3/T]
SS_O = sub-surface outflow from the lake [L^3/T]
E_O = evaporation from the lake surface [L^3/T]
S_O = surface outflow from the lake [L^3/T]
ΔV = change in lake storage [L^3/T]
P_I = direct precipitation over the lake surface [L^3/T]
S_I = surface water inflow to the lake [L^3/T]
D_I = inflow to the lake through drains [L^3/T].

Water balance approach is used to determine the unmeasured components of a lake system for a particular condition. In the unsteady flow condition the changes in storage of the lake occur over a finite interval of time and therefore, the time interval used in the equation must be large enough to overcome the uncertainty in the estimations. As, all the known components are to be estimated accurately for the selected time interval, larger time scales (monthly or annual) are better than smaller time steps (e.g. daily). Moreover, the magnitude of the computed component has to be large relative to the sum of expected errors in measurement of other components; otherwise, the error may overshadow the computed values.

Interconnection Between Nainital Lake and Downstream Springs

In order to understand the inter-relationship between the lake and the springs, hydrochemistry and isotopic characteristics have been studied. Sulphate versus chloride plots of Nainital lake and downstream Sariyatal and Balia ravine springs show clustering (Figure 2). Other downstream springs, such as those in Kailakhan area and Durgapur, show enrichment in sulphate content as compared to the lake. When total cations (TZ^+) of different springs are normalised to those of the lake, Sipahidhara spring showed little variation with time as compared to upstream springs and wells. This indicates that the lake is the main source for Sipahidhara spring. Likewise, the isotopic values of some of the springs are very much similar to the lake. $\delta^{18}O$ of Gupha Mahadev spring and the lake are -9.5λ and -9.6λ respectively. Springs located in Kailakhan area show relatively heavier $\delta^{18}O$ (-7.0 to -7.5 λ) during winter, which is comparable to $\delta^{18}O$ of the lake in summer. However, some of the springs such as S1, S6, S7, S9, S10, S11 and S12 show depleted $\delta^{18}O$ values of -10.2 λ to -11.8 □ as compared to those of the lake (-5.0λ to -9.6λ).

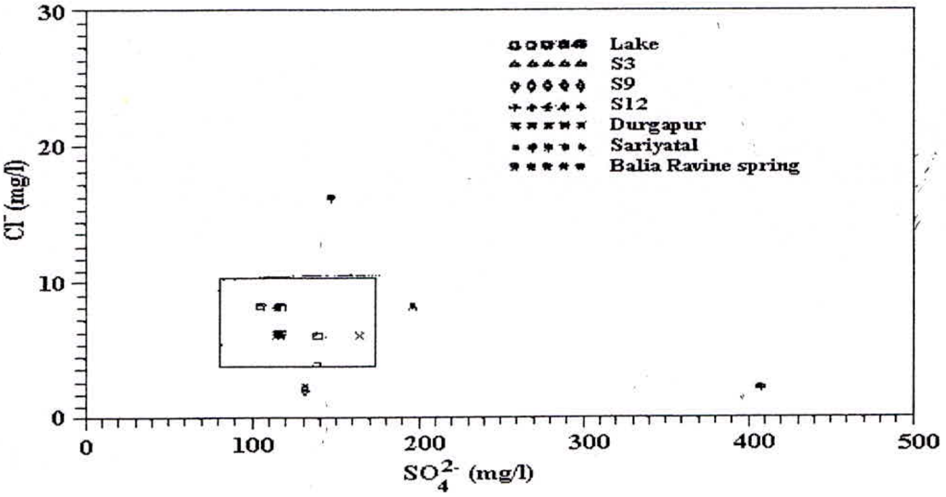

Figure 2. Sulphate-Chloride cross plot for different water sources in Nainital area

Further, samples were collected from Gupha Mahadev Temple Spring during different seasons to establish the nature of variation in $\delta^{18}O$ in relation to that of Nainital lake. The plot of $\delta^{18}O$ with time for the lake and the spring are shown in Figure 3. This plot clearly indicates that the Gupha Mahadev Temple spring issues from the lake as there is only time lag in $\delta^{18}O$ variations of the spring due to travel time.

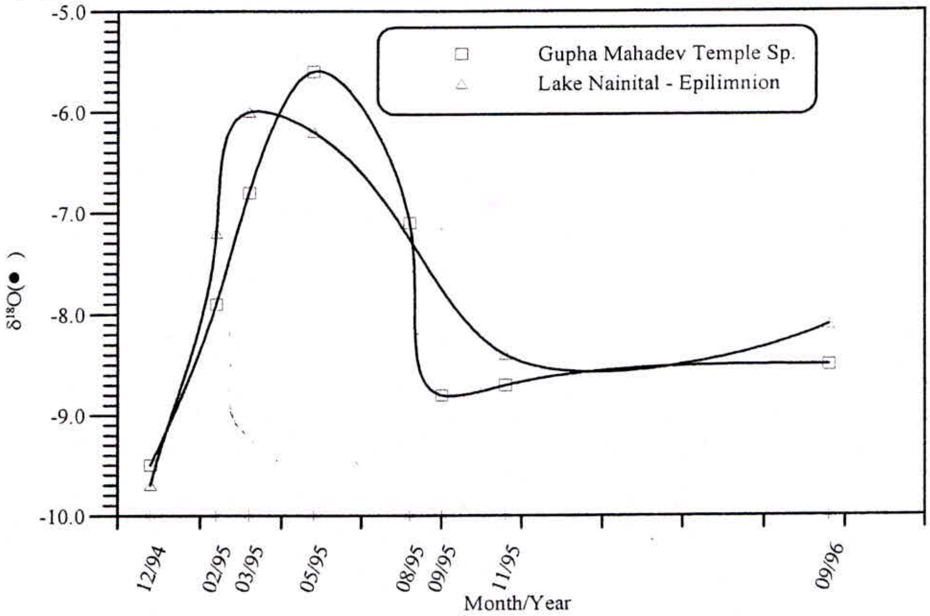

Figure 3. Temporal variation in $\delta^{18}O$ of Gupha Mahadev temple spring and Lake epilimnion zone

Conventional Water Balance Method

Monthly water balance of the Nainital lake was computed for 1994 and 1995 by conventional techniques, except for the sub-surface components. The results of the tracer technique used for estimating the outflow from the lake through pumping wells and the sub-surface outflow through springs are discussed below:

Estimation of outflow from the lake through pumping wells

The proportion of the lake water being pumped from the wells located near the lake was estimated by isotopic tracer technique using a two-component mixing model. Groundwater isotope index has been calculated from the data of upstream springs and the lake isotopic index has been calculated from volume-weighted averages data. The $\delta^{18}O$ data of admixture i.e., the well water, end-member indices along with the proportion of lake water being pumped are presented in Table 1. The results show that proportion of lake water component in the water pumped from the wells is lower in non-monsoon seasons, as compared with monsoon season.

Table- 1: Proportion of lake water in the well water being pumped (Wo) along with $\delta^{18}O$ of end-members and admixture.

Month	$\delta^{18}O$ (λ)			
	Lake	Groundwater	Well	Proportion of lake water (%)
February, 1995	-7.3	-8.2	-8.0	25
March, 1995	-7.1	-7.5	-7.4	25
May, 1995	-7.1	-7.5	-7.4	30
August, 1995	-6.3	-8.9	-6.8	80
November, 1995	-8.2	-7.9	-8.0	40

Estimation of Sub-Surface Outflow Through Springs

A number of springs are visible in the area downstream to the lake (Balia ravine). Once the interconnections of springs issuing in the downstream area are established using chemical and isotopic approaches (details are given under interconnection heading), the total discharge of the springs can be considered as the subsurface outflow from the lake. Average monthly discharges of nine downstream springs located in Balia ravine were monitored by UPPWD for the period of 1948-52. The data suggest that out of the nine springs, only Rais Hotel and Sipahidhara springs account for about 92% of the aggregate discharge. Presently, many of these springs are dry, and the discharge of Sipahidhara is considerably reduced.

The discharge data of springs reveals that there is a reduction of about 85% in the discharge of Sipahidhara spring in the past 50 years. The reduction is probably due to clogging of subterranean pathway as a consequence of lake sedimentation (Kumar et al., 1999). Mean ratio of discharge of Sipahidhara spring to the total discharge of all the springs have been calculated from the data for the period 1948-52. Total discharge of all the springs located in the Balia ravine and issuing from the lake, has been computed for the years 1994 and 1995 by using the calculated ratio and the discharge of Sipahidhara spring observed in 1995.

Estimation of sub-surface inflow

Once the subsurface outflow through springs is determined, the subsurface inflow component to lake can be calculated. The calculated values for each component of monthly water balance for the years 1994 and 1995 along with standard error are presented in Table 2. Groundwater inflow to the lake (**SS_i**) and the standard error in the estimation of groundwater inflow (**σ_{SSi}**) have been calculated by the following equations:

$$SS_I = (E_O + S_O + W_O + SP_O + \Delta V) - (P_I + S_I + D_I) \qquad \ldots\ldots (2)$$

$$\sigma_{SSi} = [\sigma_{Eo}^2+\sigma_{So}^2+\sigma_{Wo}^2+\sigma_{SPo}^2+\sigma_{\Delta V}^2+\sigma_{PI}^2+\sigma_{SI}^2+\sigma_{DI}^2]^{½} \quad \text{......} \quad (3)$$

Table 2. Estimates of different water balance components (x10^3 m^3) of Nainital lake for the years 1994 and 1995 along with standard error in the estimates.

Year	ΔV	P_I	D_I	S_I	S_o	E_o	W_o	SP_o	SS_I
1994	-29± 37	631 ±32	772 ± 36	827± 110	1570± 57	564 ± 26	1582± 52	783± 37	2240 ± 154
1995	49± 58	805± 40	772± 36	1491± 174	2025± 63	575± 26	1798± 58	783± 37	2162 ± 214

It is seen from the results that the absolute error in groundwater inflow varies for monthly estimates, but for the annual estimates of groundwater inflow to the lake it is around 10%.

Isotope mass balance Method

Isotope mass balance of a lake may be written as

$$\delta\Delta V = (\delta_P P_I+\delta_{Si}S_I+\delta_{Di}D_I+\delta_g SS_I)-(\delta_E E_O+\delta_{So}S_O+\delta_L SS_O) \quad \text{......} \quad (4)$$

Equation (4) can be rearranged to get sub-surface terms:

$$\delta_g SS_I-\delta_L SS_O =(\delta_E E_O+\delta_{So}S_O''\delta\Delta_L V) -(\delta_P P_I+\delta_{Si}S_I+\delta_{Di}D_I) \quad \text{.....} \quad (5)$$

Where, SS_I, SS_O, E_O, S_O, P_I, S_I, D_I and ΔV are as given in Equation (1) and δ_g, δ_{Go}, δ_E, δ_{So}, δ_P, δ_{Si}, δ_{Di} and δ_L are the corresponding isotopic values. Rearranging

Equation (2) and solving simultaneously with Equation (5), we get:

$$SS_O=\frac{[\delta_G(S_O+E_O\pm\Delta V-S_I-D_I-P_I)-(\delta_L S_O+\delta_E E_O\pm\Delta\delta_L V-\delta_P P_I-\delta_D D_I-\delta_S S_I)]}{(\delta_L-\delta_G)} \quad \text{.....} \quad (6)$$

The above equation is used to determine the sub-surface outflow component of the lake, which in turn is used to estimate groundwater inflow to the lake by the following relation:

$$SS_I = [(E_O + S_O -\Delta V)-(P_I + D_I + S_I)]+ SS_O \quad \text{......} (7)$$

This method of estimation does not require prior estimation of the outflow from the lake through springs and pumping wells.

Isotope mass balance has been attempted for the period between February, 1994 and February 1995. Since in the month of February, the lake remains well mixed and homogeneous, it eliminates the stratification effects on the calculation. The mean $\delta^{18}O$ values of the lake considered for mass balance are -8.2‰ (February 1994) and -7.3‰ (February 1995) with a net change of 0.9‰. The $\delta^{18}O$ values for different components are precipitation -11.3‰, evaporation -29.1‰, surface inflow -8.6‰ and inflow through the drains -8.0‰. The $\delta^{18}O$ of surface outflow is taken as -8.0‰ as surface outflow occurs mostly at higher lake water levels and with higher surface inflow, having less time for proper mixing. This is shown by the values observed during September 1996, when the surface layers were comparatively depleted than the bottom water. The $\delta^{18}O$ value of groundwater inflow is -9.0‰ and that of the subsurface outflow from the lake is -8.0‰. Sub-surface outflow (SS_O) of the lake calculated by isotopic mass balance method is presented in Table 3. The results are used in Equation (7) to compute groundwater inflow (SS_I) to the lake. The results indicate that sub-surface components are dominant over other components. The SS_I and SS_O account for 51% and 56% of total inflow and total outflow respectively.

The isotope mass balance method is sensitive to the difference between the $\delta^{18}O$ values of groundwater inflow and that of the lake seepage. The relative error decreases with increase in the difference between these two isotope indices used. In a similar study, the investigators (LaBaugh et al., 1997) have considered uncertainty in the sub-surface components of the lake - not based on the classical propagated error estimation approach, but based on the errors in the conventional (flow-net) method. Therefore, in the present investigation also, a similar approach has been adopted and a conservative estimate of 10% (estimated for the water balance method) is considered as uncertainty in the estimation of sub-surface components by isotope mass balance method.

Chloride Mass Balance Method

Mass balance can be attempted by means of conservative chemical constituents. among the various chemical constituents, chloride is a conservative species, and therefore, it may be used for such studies. the advantage of the chloride mass balance over the isotope mass balance method is that the mass of chloride loss from the lake through evaporation is zero. therefore, it is much simpler as compared to isotope mass balance. however, chloride may be introduced into the lake and groundwater systems through anthropogenic activities and becomes disadvantageous. in the present work chloride mass balance has been attempted for the purpose of comparison.

The concentration of chloride in lake water was 8 mg/L and 10 mg/L during February 94 and 95 respectively. The mean concentration in drain water (D_I) was 31 mg/L, and that in surface inflow (S_I) was 24 mg/L. The latter value has been used considering the fact that during monsoon period the flow in the drain water, particularly during the sampling period, was dominated by channeled surface runoff. The mean concentration of chloride in groundwater was 16 mg/L in the upstream springs viz., Pardhadhara, Alma cottage and Lakeview springs. The mean chloride concentration of the downstream springs, Sipahidhara and Gupha Mahadev Temple (7 mg/L), has been considered as representative of subsurface outflow from the lake. The input of chloride by precipitation has been considered as 1 mg/L, by interpolating the data pertaining to Lucknow (Handa et al., 1984) and Srinagar (Maske and Nand, 1982) stations.

Sub-surface outflow (SS_O) from the lake, computed using the chloride mass balance approach has been presented in Table 3. The result has been used in Equation (7) to compute sub-surface inflow (SS_I) to the lake. The results corroborate the findings of conventional water balance method i.e., the sub-surface components are dominant over other components. The SS_I and SS_O

computed using the chloride mass balance method account for about 55.0% of total inflow and about 59.0% of total outflow respectively. As compared with the estimates of conventional water balance, the SS_O computed by chloride mass balance method is higher by 5%.

Comparison of Results

The results presented in Table 3 show that the estimates of sub-surface inflow to the lake and outflow from the lake, obtained through isotopic and chemical balance, compare well with those obtained through conventional water balance method.

`No table of contents entries found.` Table 3. SS_I and SS_O data estimated by isotopic, chemical and conventional mass balance methods.

Method of estimation	$\delta^{18}O$ (‰)		Chloride		Conventional	
	SS_I	SS_O	SS_I	SS_O	SS_I	SS_O
Volume (x 10^3 m^3)	2269	2618	2777	3140	2234	2416
% to total inflow or outflow	51	56	55	59	50	54
Lake WRT -Year *	1.93		1.77		1.92	

* In Table 3, Lake water retention time has been calculated, assuming mean depth of the lake as 18.52 m. Time difference between the dates of sampling considered was 380 days. Appropriate corrections have been made to calculate the total inflow in 365 days.

ESTIMATION OF SEDIMENTATION RATE

Radiometric Dating Method

The sedimentation rates have been estimated at different locations in the lake employing Cesium-137 (Cs-137) and Lead-210 (Pb-210) radiometric dating techniques of sediments. Radiometric dating techniques have been proved as reliable tools for estimation of lake sedimentation rate and are being used the world over. Although several radioisotopes are useful in geochronological studies of lake sediments, ^{210}Pb and ^{137}Cs find wider application. ^{210}Pb dating technique was initiated by Goldberg (1963) and the technique was established for dating of lake sediments by Krishnaswamy et al. (1971). Since then numerous studies on the use of ^{210}Pb and ^{137}Cs both in the research and application fronts of lake sediment dating have been reported (Robbins and Edgington, 1975; Krishnaswamy and Lal, 1978; Ritchie and McHenry, 1985; Walling and He, 1993).

In order to estimate the sedimentation rate and life of Lake Nainital using radiometric sediment dating techniques, sediment cores were collected from different parts of the lake with a gravity corer. The length of collected cores ranged from 42 to 57 cm. Of these cores, three cores (Fig. 1) viz. Q, S & V which were considered to be representative of lake's sedimentary environment were subjected to radiometric dating. The cores were sliced into 2 cm sections and analysed at Bhabha Atomic Research Centre, Mumbai, India, for ^{210}Pb and ^{137}Cs activities. The profiles of ^{210}Pb and ^{137}Cs activities in different sediment cores with respect to depth are shown in Figure 4. The details of measurements of ^{210}Pb and ^{137}Cs activity and models used including assumptions made in the interpretation of ^{210}Pb are presented by Saravanakumar et al. (1997). The standard counting error in case of ^{210}Pb method was generally less than 10% in the upper sections of the cores and slightly higher at the deeper sections. In case of ^{137}Cs, the standard counting error was less than 10% in the core sections.

At the sampling location 'Q', the ^{137}Cs profile closely paralleled its weapon fall-out record pattern reported by earlier investigators (McHenry et al., 1973; Livingston and Cambray, 1978) i.e., an initial appearance in 1952-53; a subsidiary peak in 1957-58; and a major peak in 1963-64. With the depth corresponding to 1963-64 as time marker, the average sedimentation rate (both in linear and mass units) of Lake Nainital was computed and is listed in Table 4. The close similarity in the deposition and fall-out pattern of ^{137}Cs probably indicates that the residence time of ^{137}Cs in the lake water is small and post-depositional mobility of the radionuclide in the sediment core, if any, is insignificant. However, the ^{137}Cs profile of Lake Nainital may be viewed as an ideal case. Due to short length of the core obtained, the initiation and subsidiary peaks of 1952-53 and 1957-58 are not clearly seen in core samples 'V' and 'S' respectively (Fig. 4).

The sedimentation rate obtained by ^{210}Pb in different parts of the lake varies from 0.48 cm/yr to 1.24 cm/yr while in case of ^{137}Cs, it varies between 0.60 cm/yr and 1.35 cm/yr (Table 4). The sedimentation rate is higher (1.15 cm/yr and 1.24 cm/yr) in the intermediate portions located just adjacent to the bank zones while comparatively moderate (0.64 cm/yr) in steeper bank zones. The deeper portions, away from the bank of the lake, receive sediment at a lower rate (0.48 cm/yr). The average sediment accumulation rate as determined by radiometric dating method is 0.75 cm/yr. It is very encouraging that the results obtained by radiometric dating techniques compare very well with that obtained by sediment balance method (Table 8).

The sedimentation rates have been estimated using radiometric dating by other investigators for a few other Kumaun lakes (Das et al., 1994; Kusumgar, et al., 1989). In the case of Lake Bhimtal the sedimentation rate reported by Das et al. (1994) compares well with that of Kusumgar et al. (1989). Since the technique gives comparable results (considering the error limits), the results (1.15 cm/yr) reported by Das et al. (1994) have also been used (point D in Fig. 1) in computing the life of Lake Nainital. It is interesting to note that the mean sedimentation rate in Lake Nainital (0.75 cm/yr) is comparatively higher than in other lakes (Lake Bhimtal: 0.47 cm/yr & 0.68 cm/yr; Lake Naukuchiatal: 0.37 cm/yr; Lake Sattal: 0.39 cm/yr) of this region (Kusumgar et al., 1989; Das et al., 1994). This is probably because unlike other lakes of the region, Lake Nainital is surrounded by carbonate rocks which are highly susceptible to weathering. The estimated sedimentation rates as well as the models adopted for interpretation of ^{210}Pb activity data are presented in Table 4. ^{210}Pb sedimentation rates (in linear and mass units) take into account the effect of compaction, Das et al. (1994).

Table 4: Sedimentation rates and inventories of ^{210}Pb and ^{137}Cs in Lake Nainital.

Sample Code	Average sedimentation rate				
	^{210}Pb			^{137}Cs	
	Model used	Linear (cm/yr)	Mass ($g/cm^2/yr$)	Linear (cm/yr)	Mass ($g/cm^2/yr$)
V	CFCS	0.48±0.04	0.112±0.010	0.60±0.07	0.140±0.016
Q	CF	0.64±0.18	0.150±0.041	0.70±0.03	0.168±0.007
S	CF	1.24±0.44	0.289±0.104	1.35±0.05	0.315±0.018

CFCS- constant flux (^{210}Pb) and constant rate of sedimentation; CF- constant flux

Constant Initial Concentration (CIC) Model

$$C_d = C_0 e^{-lt}$$

where, C_d = concentration of ^{210}Pb at depth dC_0 = concentration of ^{210}Pb at the surface l = decay constant for ^{210}Pb (0.03114) t = life of sediment at depth d. [$t = d / r$], r = Sedimentation rate d = depth of sediment sample in a sediment core.

Constant Rate of Supply (CRS) or Constant Flux (CF) Model

$$A_d = A_0 e^{-lt}$$

where A_d is the unsupported ^{210}Pb in the core below depth 'd' and A_0 is the entire unsupported ^{210}Pb below the mud/water interface. The varying sediment accumulation rate r can be calculated from $r = A_d / C_d$ where C_d is the unsupported ^{210}Pb concentration.

Constant Flux and Constant Rate of Sedimentation (CFCS) Model

$$C = C_o e^{-km/r}$$

where C_o is the unsupported ^{210}Pb concentration at the sediment – water interface, r is the dry-mass sedimentation rate and k is the decay constant of ^{210}Pb. (k=0.03114/yr).

Sediment Balance Method

Sediment inflow to the lake has been monitored at the two major inflow points to the lake. It has been observed that the average SS concentration during normal days is about 0.41 g/L and during rainy days is about 1.25 g/L. This information coupled with daily inflow gives the total sediment input into the lake. The sediment outflow from the lake has been computed using the discharge from the lake through the sluices and the average SS concentration in the epilimnion (0.55 g/L). The detailed sediment balance has been presented in Table 5.

COMPUTATION OF LAKE LIFE

In lakes, the inflow velocity and other forces such as gravitational force and the secondary forces of flow turbulence control the spatial distribution of incoming sediments. Wiebe and Drennan (1973) and Sly (1978) recognised three generalized zones of sediment distribution and sedimentary processes in lakes. However, keeping in view the geomorphological features, underwater topography, core recovery and spatial variation observed in the sedimentation rates, Lake Nainital has been divided into four zones (Fig.5). The lake life has been estimated taking into account the estimated sediment accumulation rates in all the four zones and the present volume of the lake.

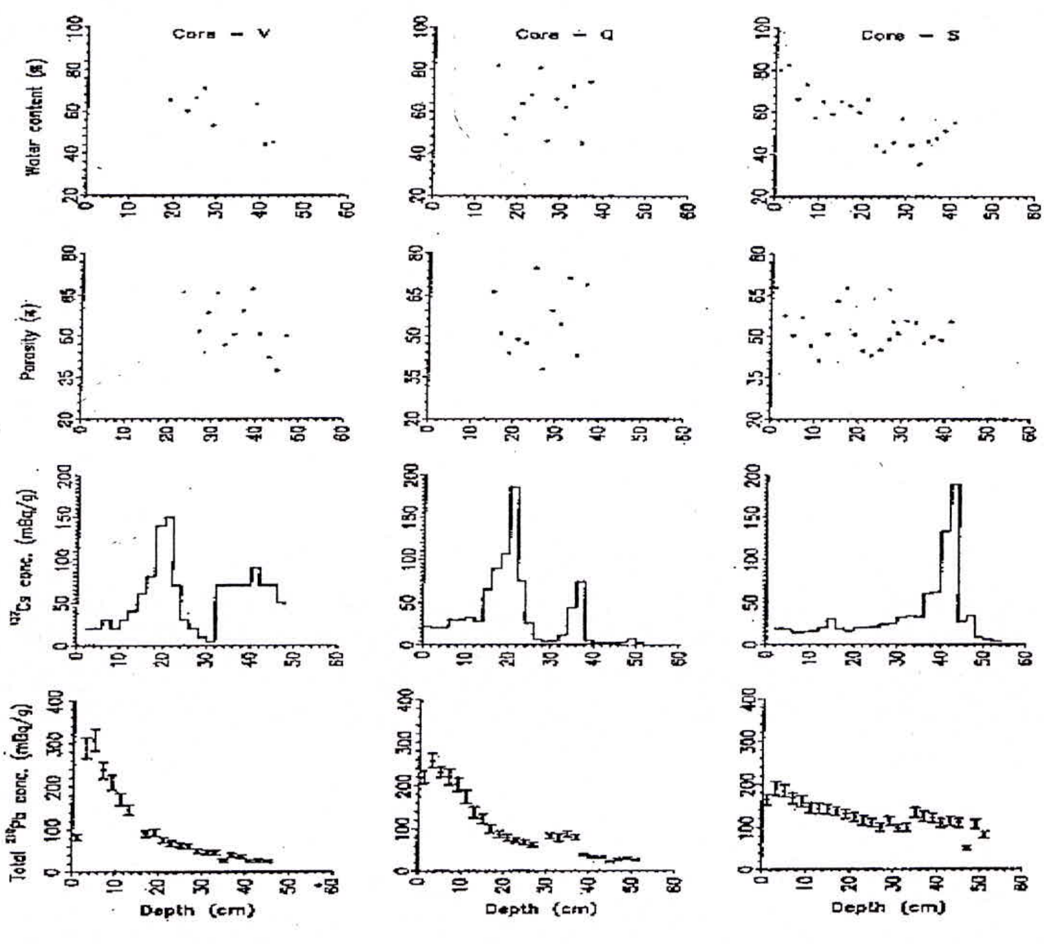

Figure 4. ^{210}Pb and ^{137}Cs activity profile in three representative core samples along with moisture content and density.

Table 5: Rate of sediment accumulation estimated by sediment balance method

	Suspended Sediment Concentration	Total Suspended Sediment load (m^3)
Inflow through drains and during light rains	0.41 g/L	1500
Inflow during heavy rains	1.25 g/L	5097
Outflow through sluices	0.55 g/L	3422
Inflow - Outflow (sediment accumulation rate)	-	3175 (0.69 cm/yr)

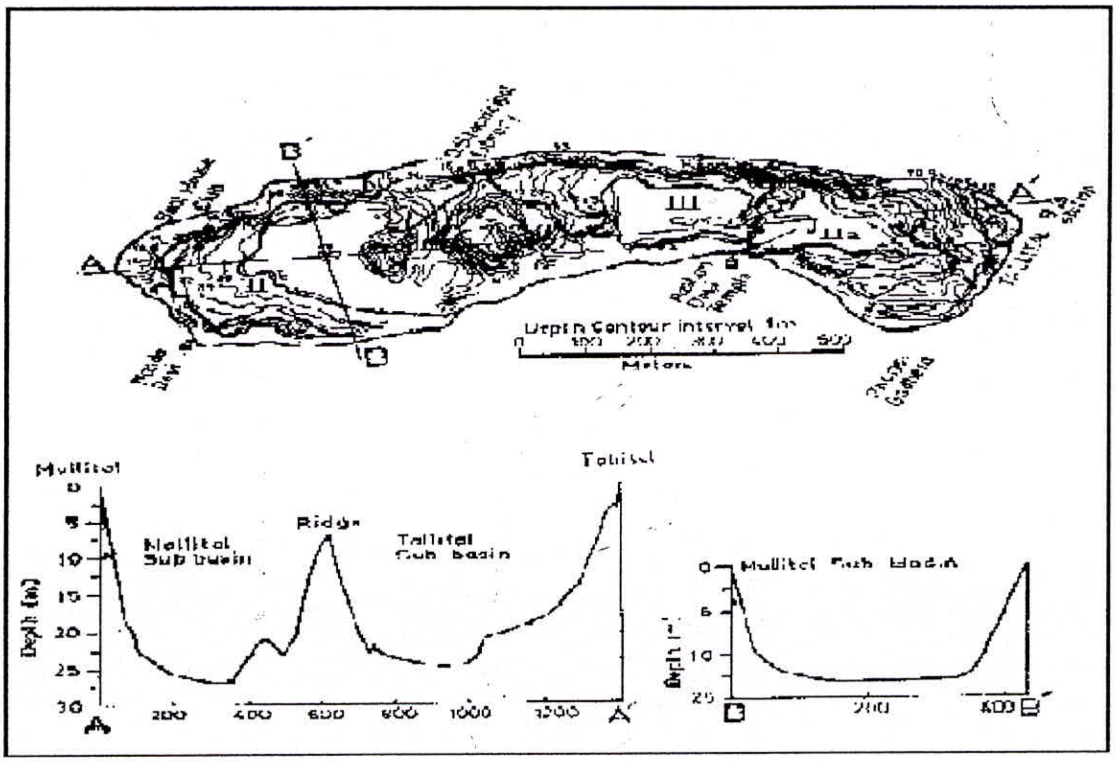

Figure 5. Nainital lake bathymetry and four different zone of deposition with the cross sections showing the present bottom configuration of the lake.

The total sedimentation in Lake Nainital, taking into account the mean accumulation rates in all four zones, is 3462 m^3/yr (^{210}Pb) and 3901 m^3/yr (^{137}Cs). If the sediment deposition continues at the same rate, the lake may completely be filled up in 2160±80 years (^{137}Cs) or 2480±310 years (^{210}Pb) under normal environmental conditions. Considering the error limits of the life estimated by both the methods, the mean lake life is around 2200 years, which is in stark contrast to the results (Table 6) of earlier investigators.

The useful life of the lake estimated by radiometric dating techniques and sediment balance method is given in Tables 7 and 8 along with standard error. The standard errors were computed from an analytical expression presented by Saravanakumar et al. (1999) and Das et al. (1994).

The earlier investigators, who perused the UPPWD lake sounding data, chose to analyse the data pertaining to a selected period only, which showed sediment accumulation. As mentioned earlier, Hukku et al. (1968) have pointed out the problem of anomalous data which indicated bi-directional variation in the lake volume. Further, the lake volume computed using the bathymetric data collected with echo-sounders and advanced positioning systems (Hashimi et al., 1993) does not compare with that computed using UPPWD data.

Table 6: Expected life of Nainital Lake estimated by earlier investigators using UPPWD lake sounding data

Period Selected for Study	Method of Estimation	Predicted Life (Yr)	Investigators
1960 - 1966	Mean siltation and Area	82	Hukku et al. (1966)
1965 - 1975	-do-	314	Sharma (1981)
1895, 1969 & 1979	Contour	380	Rawat (1987)

Table 7: Estimation of lake life using radiometric dating of sediments

Radio-isotope	Lake Zone	Area (m^2)	Sedimentation rate (cm/yr)	Sediment accumulation rate (m^3/yr)	Estimated lake life (yr)
^{210}Pb	I	163036	0.64±0.18	1043±293	2480±310
	IIa	70597	1.24±0.44	875±311	
	IIb	65916	1.15±0.09	758±66	
	III	163815	0.48±0.04	786±59	
^{137}Cs	I	163036	0.70±0.03	1141±49	2160±80
	II	136513	1.35±0.05	1843±68	
	III	163815	0.60±0.07	983±115	

Table 8: Average sediment accumulation rate and lake life estimated by different methods

Method of Estimation	Average rate of sediment accumulation		Lake Life (years)
	m^3/yr	cm/yr	
Sediment Balance	3175	0.69	2700
^{210}Pb dating	3460	0.75	2480
^{137}Cs dating	3970	0.86	2160

Ritchie and McHenry (1985) while comparing ^{137}Cs dating method with bottom contour method for measuring rates of sediment accumulation recommended the ^{137}Cs method for a quick and accurate estimates of sediment accumulation since 1954. Ritchie and McHenry, further point out that it is crucial to know the control points for the survey lines for the success of the bottom contour method. In case of Lake Nainital, probably the improper recording of the bathymetric data with respect to the control points, which is reflected by the variation of the number of data points in each section in different years.

Further, in order to determine the soil erosion from the catchment by using sedimentation rates in the lake, the total sedimentation in a lake (in m^3/yr) can be divided by the total catchment area of the lake (in km^2). The followoing example can be taken.

The average sedimentation rates estimated using Cs-137 and Pb-210 dating techniques in different lakes of Western Himalayan Region are given below.

Name of Lakes	Average Rate (cm/y)	Average Life (yrs)
Naini	0.81 ± 0.05	2200 ± 190
Bhimtal	1.44 ± 0.18	661 ± 94
Naukuchiyatal	0.74 ± 0.04	3161 ± 281
Sat-Tal	0.84 ± 0.05	1357 ± 126
Dal-Nagin	0.22±0.03	360± 80
Nagin	0.34 ±0.03	376± 50
Mansar	0.23 ± 0.02	9110 ± 790

The soil erosion rates estimated from Mansar lake catchment is 1247 m^3/km^2/yr, followed by 936 m^3/km^2/yr in Nainital, 772 m^3/km^2/yr in Naukuchiatal, 666 m^3/km^2/yr in Bhimtal, 495 m^3/km^2/yr in Dal-Nagin, and 386 m^3/km^2/yr in Sat-tal lake.

The estimated useful life of Dal lake is shorter among all the lakes that have been studied. This is because the size of the Dal-Nagin lake catchment is comparatively larger than the catchment of Mansar lake, while the rate of soil erosion is highest in the Mansar lake catchment. It seems to be justified because the Mansar lake catchment fall in the Siwalik Himalayas where the rocks (sandstone interbedded with clay) are very fragile and prone to high soil erosion.

HYDRODYNAMICS

During the collection of water samples in May, October and December 1994 and February, March, May, June, August, September and November 1995 from different depths and locations of the lake for environmental isotope analysis (δ18O and δD and 3H), in-situ measurements of physico-chemical parameters including Temperature (T), Dissolved Oxygen (DO) and Electrical Conductivity (EC) were also done.

The monthly depth-wise distribution of environmental isotopes (both deuterium and oxygen-18), along with in-situ physical & chemical parameters of the lake water are shown in Fig. 6. From the figures, it is clearly seen that the change in the in-situ physical & chemical parameters as well as the isotope contents with depth show correlative trends. The lake is stratified for 7 to 9 months in a year (i.e., from March/April to October/November). The stratification builds up quickly in March and is very strong in summer. During the stratified periods, the metalimnion (i.e. the region of relatively rapid change of temperature) is seen at a depth of 3 m from the free surface during the months of March/April to June/July and at a depth of 6 m from the free surface during the remaining periods of the stratification. The winter overturn is in November and since then the lake is well mixed for 3 to 4 months (i.e. from November/December to February/March). During the well-mixed condition the whole water mass or just parts of it circulate if there is enough wind. The EC of lake waters, during stratified periods and during the well-mixed periods, is nearly constant. Therefore, it appears that the stratification seen here is, by and large, a thermally induced one and not by solute concentration. The uniform tritium content of the lake during the reconnaissance survey in May 1994 (i.e. about 11.2 ± 0.5 TU) gave a clear indication, in advance, that the stratification seen during summer months could be seasonal and the lake is expected to be well-mixed during winter.

The vertical distribution of all the above parameters (Fig. 6) indicates higher values at a few deeper points. This may be due to the groundwater recharge (in the form of underwater springs) at those points & depths. Most of the inferred groundwater recharges are seen near the submerged ridge in the center, through the major fractures in the north-east of the lake boundary, along the existing fault plane and near the existing dyke in the southwest sub-basin (ref. Fig. 1). In addition to poor vertical mixing of the lake due to stratification during the summer months, poor horizontal mixing is also seen from the horizontal distribution of the above parameters.

The isotopic composition of hypolimnion does not remain the same during the period of stratification, and also the δ values of hypolimnion and those of the epilimnion are not correlated well. This probably indicates that the water retention time of the lake is very short and lack of correlation between the δ values of hypolimnion and epilimnion indicate independent inflow components to the two regions. Also the lake-groundwater system appears to be a flow-through type.

From the $\delta^{18}O$ - δD plot of the epilimnion lake waters (during stratified periods) and lake waters (during well mixed periods), only centrally located samples (along the longitudinal axis) of the lake during stratified periods (Fig. 7) fall on an evaporation line (EL):

$\delta D = 4.3\ \delta^{18}O + 18.4$ (n=6, r=0.97, significant at 0.05 level) .... (8)

The remaining samples fall on the local meteoric water line (LMWL).

$\delta D = 7.4\ \delta^{18}O + 5.4$ (n=6, r=0.98, significant at 0.05 level) ...... (9)

This may be because under the condition of poor horizontal mixing (as mentioned earlier), the sampling locations near the contact area of the lake (i.e. boundary between the lake and its groundwater) will have the maximum groundwater contribution and thus these samples represent lake waters diluted by groundwater and therefore, they fall on LMWL.

However samples from C2 and E1, (Fig. 1) even though centrally located, do not fall on EL during stratified months but fall on LMWL with some seasonality. This may be because, as seen from the geology map of Lake Nainital (Fig. 1), location C2 is probably influenced by the groundwater discharge to the lake, which is mainly controlled by the presence of a doleritic dyke. The groundwater flow along the dyke, which is basically a delayed component of precipitation, appears to be unsteady with little flow during the months of February, March, and April and thereby the isotope values of C2 samples during these months represent pure lake water and thus fall on the EL. Since location E1 is near the ridge, there is a possibility of groundwater recharge and thereby its isotope values also fall on LMWL.

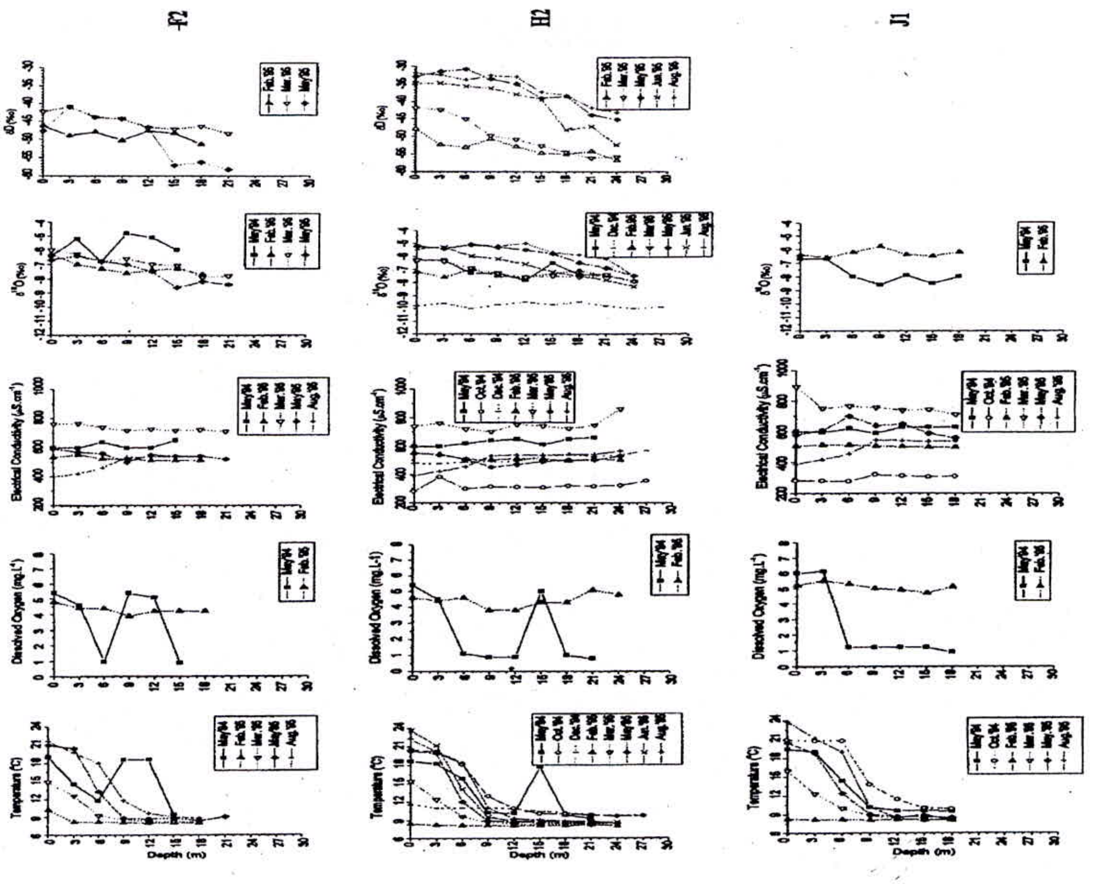

Figure 6. Monthly vertical distribution of environmental isotopes and in-situ physical and chemical parameters of the lake waters at few representative locations at F2, H2, and J1

In lakes, the vertical component of water transport is of prime interest to the understanding of mass flux and mass balance. The presence of the submerged transverse ridge about 8 m below the lake surface has an important control on the dynamics of the lake. Its presence inhibits the mixing of deeper waters of Mallital with Tallital and thus the hydrodynamics of the two sub-basins are different. This is confirmed by the slight variations in the levels of all the parameters under discussion, particularly at deeper depths (Figs. 6). The stratification in the lake has profound consequences on the physical, chemical and biological phenomena in the lake. For example, aeration occurs in the epilimnion, while in the hypolimnion anaerobic conditions prevail.

The turnover period or water retention time of the lake, as estimated using Isotopic mass balance method, chloride mass balance method and conventional water balance method (Table 3) is about 2 years. It indicates that due to faster replenishment of lake water, the lake water should not develop any type of pollution. However due to different types of solid wastes that are only partial soluble in water get settled at the bottom and become active during the mixing of epilimnion and hypolimnion portions of the lake. Also, the lake remains stratified during the rainy season during which the maximum water is drained out from the lake, thus mostly fresh water is drained out and pollutants remain in the hypolimnion portion.

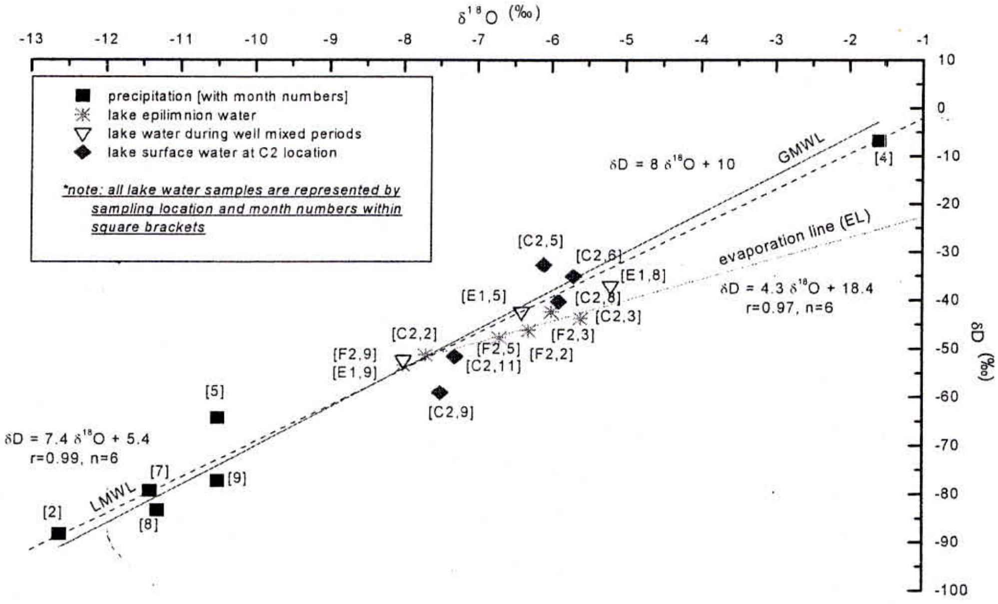

Fig. 7. Plot of δD vs. δ^{18}O of Lake Nainital with respect to GMWL and LMWL

CONCLUSIONS

Interconnections

The temporal variation in δ^{18} O, Cl^- and SO_4^{+2} and total cations indicated that springs Sipahidhara, Guphamahdev Temple, and S2, S3 and S4 springs located downstream to the lake have hydraulic connections with the lake. However, some of the springs such as S1, S6, S7, S9, S10, S11 and S12 show depleted δ^{18}O values of -10.2 ‰ to –11.8 ‰ as compared to those of the lake in the same period . More depleted values indicate different sources for the springs and at the same time suggesting that there is no hydraulic conductivity between these springs and the Nainital lake. Further, the stable isotopic composition interpreted for lake water, groundwater and the water pumped by the deep tube-wells installed near the northern bank of the lake revealed that the pumped water contains lake water fraction that varies from 25 to 80% in different months.

Water Balance

Studies carried out using conventional water balance, isotopic mass balance and chloride mass balance approaches reveal that the sub-surface contribution through annual inflow to the Nainital lake is between 46% and 61% and annual outflow from the lake is between 49% and 65%, suggesting that the lake is a 'flow - through' type with substantial inflow from groundwater and outflow through lake seepage. The presumption made in the conceptual models substantiates the usefulness of the environmental tracer techniques to study the hydraulic connectivity between the lake and downstream springs. The isotope and chloride mass balance approaches yielded comparable results for the Nainital lake area due to their closed system behavior and also due to less anthropogenic activity, unlike in many other lake environments.

Sedimentation and useful life of the lake

Sedimentation rates, estimated using past 36 years lake sounding data for different selected time intervals, vary from 3.02 (1960-1975) to 24.39 (1965-1970) cm/yr, and 4.53 cm/yr during the time span 1985-1996 depending upon the time span selected. However, the detailed analyses indicated that large bi-directional variations in the annual bathymetry implying that major errors are associated in the lake sounding data collected by U.P. PWD. The sediment balance method indicated the present sedimentation rate as 0.69 cm/yr. The radiometric dating of sediment, employing Cs-137 and Pb-210 dating techniques, revealed sedimentation rates varying from 0.48 to 1.35 cm/yr, depending upon the location of sediment cores in the lake (average 0.75 cm/yr by Cs-137 and 0.86 cm/yr by Pb-210 dating techniques).

As per the earlier investigators, the predicted useful life of the lake, estimated using the bathymetric sounding data collected manually by U.P. PWD, vary between 82 years to 380 years.

The useful life estimated by the authors using U.P. PWD lake sounding data for different time span vary from 39 years (using 1990-1993 data) to 590 years (using 1960-1975 data). The useful life estimated by sediment balance method comes around 2681 years. The useful life estimated by the radiometric dating (^{137}Cs and ^{210}Pb) of sediment cores collected from the different locations in the lake is about 2200 years under the normal environmental conditions. This age of Lake Nainital has been determined ignoring the deposition of sediments at the entry points of drains into the lake (can be removed every year) and the landslides that may occur in future in the Nainital lake catchment.

Hydrodynamics

The lake remains stratified from March to October/November and well mixed during the winter months (November/December to February) every year. During stratification, the two sub basins (north & south) behave differently, but during winter the difference disappears. The horizontal mixing in the lake is poor.

The statistical analysis of rainfall isotopic data of the basin produced the local Meteoric Water Line (LMWL) valid for Kumaun Himalaya. Similar exercise for the lake water produced a Nainital lake water line that is close to LMWL and indicates that the lake has short turnover period and the effect of evaporation is also less. The δ^{18}O and δD data of the drains vary from -7.4‰ to -9.6‰, and -44‰ to -64‰. The δ^{18}O and δD values of the drains are considerably higher than the local precipitation indicating evaporative enrichment. The slope of the δ^{18}O - δD best-fit line is -5.4, which is much less than the Local Meteoric Water Line. The δ^{18}O composition of the lake evaporates determined by indirect method is about -29.1‰.

Water retention time by isotope mass balance approach yielded 1.93 y, chloride approach 1.77 y and conventional approach 1.92y. The results by all the methods do not vary significantly from each other and compare very well within the error limits. Among these methods, the isotopic and chloride mass balance methods are more reliable, as they do not require separate estimation of outflow components by other techniques.

The management options will be discussed during the presentation.

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