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ESTIMATION OF SEDIMENTATION RATES AND USEFUL LIFE OF LAKE NAINITAL IN KUMAUN HIMALAYAS, U.P., USING RADIOMETRIC DATING TECHNIQUES

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PREFACE

Existence of Lake Nainital has been a matter of debate in the last two decades, because it is the main source of drinking water to Nainital town, a famous tourist resort in northern India. In the tectonically active lake basin, naturally occurring landslides have generated sediments in huge amount. In addition, various anthropogenic activities viz. deforestation, construction activities and improper management of wastes have reportedly aggravated the rate of sediment delivery, endangering the life span of the lake. It had been predicted by various earlier investigators that Lake Nainital is being filled up by sediments at a fast rate and the availability of lake water is being reduced and if the present rate continues, the lake will be filled up completely in 380 years.

As part of the project titled "Hydrological Studies of Lake Nainital" which was aimed to bring out relevant information and facts about different processes taking place in Lake Nainital, the rate and pattern of sedimentation in the Lake Nainital was investigated. The present report provides the results and detailed methodology of investigations carried out to estimate the rate and pattern of lake sedimentation and to use the results to predict the lake life. The rates of sedimentation have been estimated using the radiometric dating of bed sediment cores and the results are compared with those obtained by analysing the conventional sounding data as well as with those obtained by sediment balance method. The rate of sedimentation estimated using sediment balance method compares well with that obtained by radiometric method. Considering the accuracies of the methods used and validity of data used the expected life of Lake Nainital under the present environmental conditions is estimated as around 2200 years.

This report has been prepared by Dr. Bhishm Kumar, Scientist and Mr. Rm. P. Nachiappan, PRA of the Institute, with the assistance of Dr. S. P. Rai, Mr. Vinod Kumar and Mr.B.C. Dungarakoti who have worked under the Nainital Lake Project in various capacities. The contribution of Mr. U. Saravanakumar, Dr. S.V. Navada and their colleagues of BARC, Mumbai in the radiometric analysis the sediment samples and in the interpretation of the results is highly appreciated. I hope, this report will be useful to the interested investigators, engineeers and authorities associated with lake and reservoir management.

(S. M SETH)
DIRECTOR

ABSTRACT

The neotectonic Lake Nainital is the only source of drinking water supply to the city of Nainital. Publications in the recent past inferred accelerated sedimentation threatening the very existence of lake. The sedimentation rates in lake Nainital have been estimated by the authors using past 36 years lake sounding data for different selected time intervals, sediment balance method and radiometric dating of sediment cores collected from different locations in the lake. The sedimentation rates obtained by lake sounding data vary from 0.014 (1960-1975) to 0.113 (1965-1970) Mm^3/yr depending upon the time span selected while it is 0.021 Mm^3/yr during the time span 1985-1996. The sediment balance method indicated the present sedimentation rate as 0.69 cm/yr. The radiometric dating of sediment revealed sedimentation rates from 0.48 to 1.35 cm/yr, depending upon the location in lake (Average 0.75 by Cs-137) and 0.86 by Pb-210 dating techniques).

The predicted life of the lake is between 82 years to 380 years by the earlier investigators using the bathymetric sounding data, collected manually. In the present study, environmental ^{210}Pb and ^{137}Cs dating techniques have been used to estimate the lake life. Estimated life comes to be 2163 ± 77 years (^{137}Cs) and 2479 ± 312 years (^{210}Pb). If we take the Average of the life estimated by radiometric dating techniques, it comes around 2200 yr. The life estimated by sediment method comes around 2681 years while the life estimated by the authors using lake sounding data for different time span vary from 39 years, based on the data for 1990-1993 and 590 years based on the data for the period from 1960-1975. However, the critical analysis of lake sounding data implies that the validity of the data is questionable. Radiometric dating of sediment cores from appropriate areas in lakes/reservoirs provides precise record of sedimentation rate.

The details of sedimentation rate/pattern including estimation of life of lake Nainital using conventional and isotopic methods have been discussed in the present report at great length.

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1.0 INTRODUCTION

The Nainital lake is the heart of city Nainital or it will be more appropriate to say that the city came into existence only because of lake Nainital. In the past few decades, more and more construction activities have been initiated in order to cope up the continuously increasing load of tourists. These have not only increased the possibility of land slides / instability in the tectonically active area but, the forest cover has also come down considerably. All the anthropological activities have degraded the ecological environment as well as created hydrological imbalance in case of lake Nainital. The water quality of lake has also been considerably changed and the degradation of the same when realised by the intellectuals out of the public of city Nainital, they increased their voice and as a consequence, the Nainital Lake Development Authority came into existence in the year 1989 which later on renamed as Nainital Lake Region Special Area Development Authority (NLSADA) in the year 1992.

Keeping in view the alarming situation of lake Nainital as predicted by other investigators in the past, a project entitled 'Hydrological studies of Lake Nainital' was sponsored by the Department of Environment, Lucknow, Govt. of UP through NLSADA in the year 1993 in order to carry out detailed investigations. This report, on the study of sedimentation rate in lake Nainital and estimation of lake life, is based on the investigations carried out under the project.

2.0 STUDY AREA

Lake Nainital is one among a group of lakes occurring in the southern fringe of the Kumaun Lesser Himalaya (Fig. 1). The maximum length of the lake is 1.4 km, maximum width 0.45 km, maximum depth 27.3 m and mean depth 18 m. The surface area of lake is 0.46 Km^2. It is subdivided into two sub-basins by 100 m wide transverse underwater ridge, 7 m to 20 m below the lake surface while volume of the lake is 8.3 Mm^3. The Average annual rainfall in the basin is 203 mm. The catchment area of the lake is 4.9 km^2 out of which 48.4% is forest, 18.3% is barren, 19.3% is built-up area and 10.4% is water body

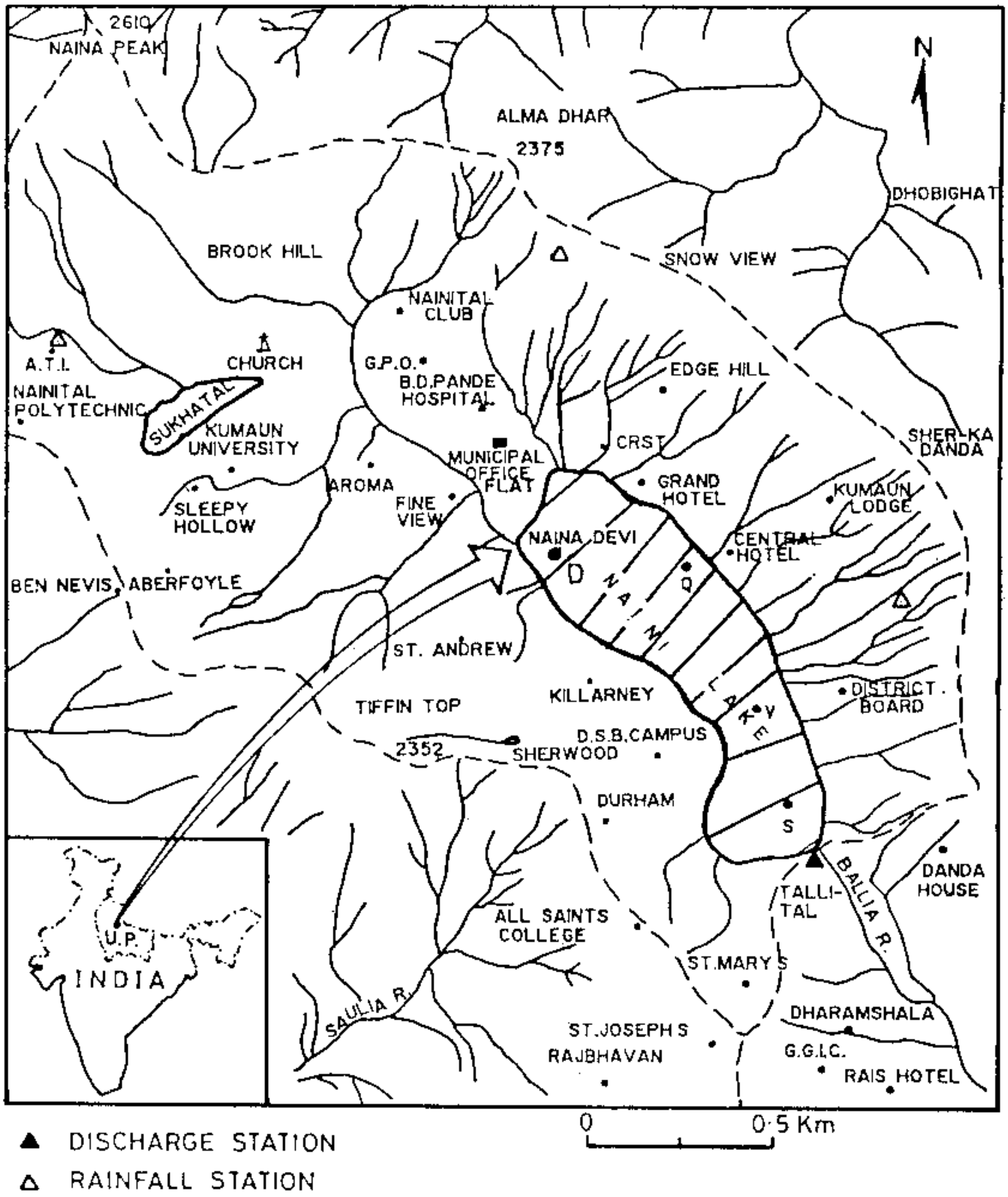

Fig. 1. Location map of Lake Nainital showing the sounding cross sections of UPPWD and the sediment core sites Q, S, V and D.

2.1 Geology and Geomorphology

Lake basin is made of completely folded and faulted rocks of Krol and Tal formations. It is diagonally cut by the Nainital fault into northeastern Sher-ka-danda - Naina Peak Ridge made up almost exclusively of the Lower Krol and the southwestern Deopatta-Ayarpatta Ridge constituted of the Middle and Upper Krol with the Tal (Valdiya, 1988). The Lower Krol consists of argillaceous limestones and marlites, while the upper Krol and Tal are made up of dolomites with limestones and black carbonaceous slates (Fig. 2).

The rotational movement along Nainital fault, passing through the basin has been the causative factor for the origin of Lake Nainital (Valdiya, 1988). The synclinal structure at Sher-ka-danda is transversed by a number of fractures tending NE-SW. The Nainital fault and these associated fracture have caused shearing and shattering of the rocks responsible for hillslope instability and attendant erosion.

3.0 SEDIMENTATION IN LAKE NAINITAL

Nainital lake is surrounded by steeply sloping ridges from three sides i. e., Sherka-Danda ridge in North-East and East, Naina Peak in the North and Ayarpatta ridge in the North-West. The high erosion rate of the surrounding hill ridges due to deforestation and other activities, mainly anthropogenic in nature, high precipitation and highly variable climatic conditions caused the sedimentation in lake at higher rate. However, the sedimentation in Nainital lake is of great concern in the past few decades as the construction of buildings for personal and commercial uses have tremendously increased which exaggerated the natural rate of sedimentation. Some of the Himalayan lakes, for example Dal lake in Kashmir, have reached a critical life of shrinking due to faster rate of sedimentation and eutrophication.

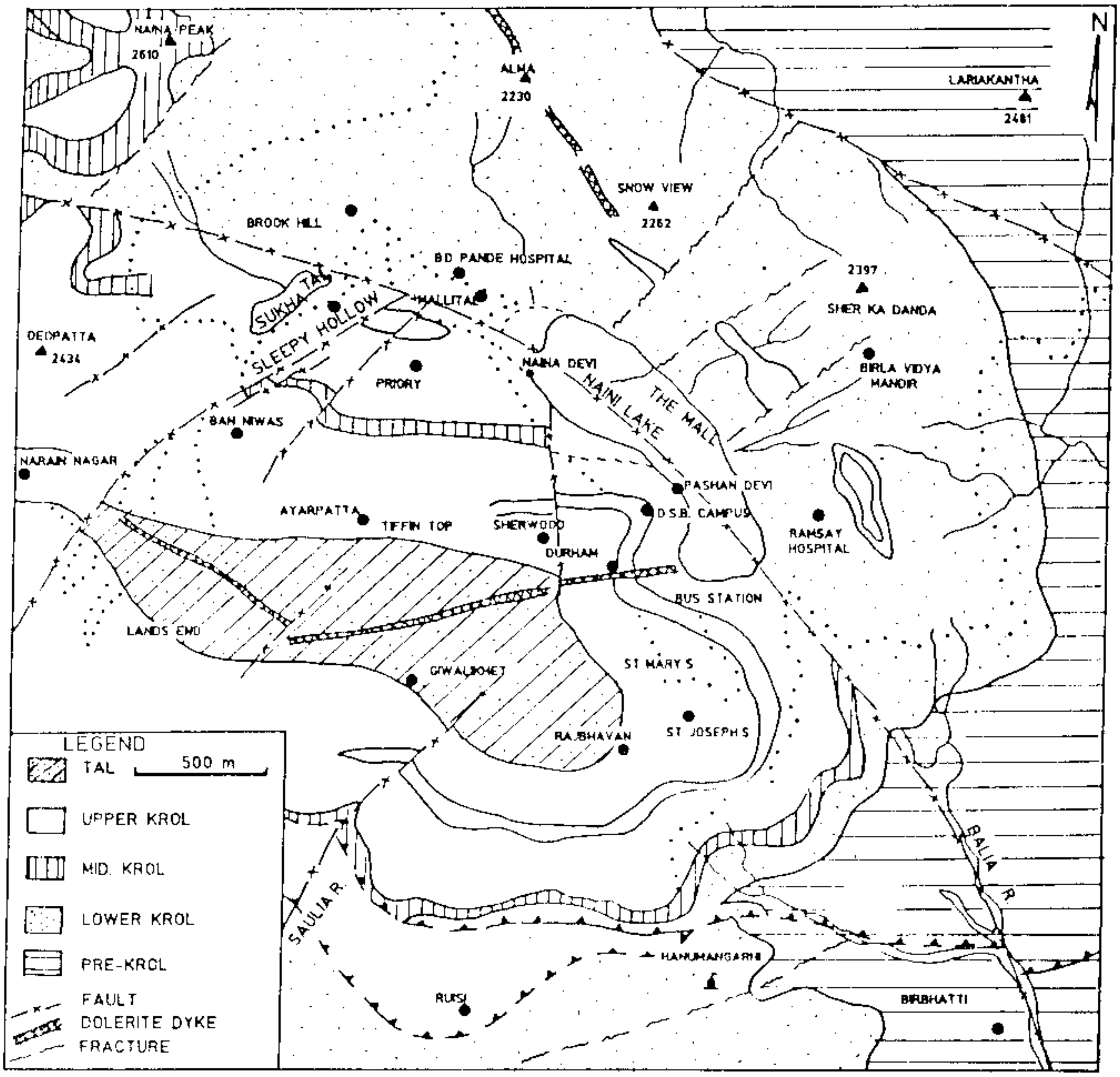

Fig. 2. Geological map of the Nainital Lake Basin showing its much faulted nature (After Valdiya, 1988).

Development of debris fans at the months of gullies descending into the lake have verified that the lake is being continuously filled with detritus material. The investigations carried out by various researchers in the recent years have revealed the fact that the lake is being filled up at a fast rate and if the present sedimentation rate is continued, the life span of the lake is not more than 300 to 400 years. As the Nainital lake is the main source of drinking water for Nainital town and surrounding areas, attraction for tourists and beauty spots, the survival of Nainital lake is directly related with the existence of Nainital city.

3.1 Causes of Sedimentation

The much faulted and folded Nainital lake basin is naturally in unstable condition. The neotectonic activities along Nainital fault and main boundary thrust has accelerated the erosion and recurrent mass movements. The human activities related with unplanned construction of multi-storied buildings at high slopes, have resulted high erosion and the construction material including house/kitchen wastes directly reaches into lake during the rainy season. The natural protection provided by oak trees has diminished, as trees have been brazenly felled or looped to death.

Mass movements has generated huge landslide debris fans, mainly the entire North-Western part of the township is located on a succession of landslide debris fans, originating from the Naina- Snow View sector of the ridge. During the years 1867 and 1880, large land slides have taken place along this sector. The 1867 - landslide gave rise to the debris fan on which the Nainital club is situated . The immediately adjacent slope to the North-East failed disastrously on Sept. 18, 1880 after a prolonged (36 hours) heavy rainfall (84 cm between 16 & 19 Sept., Oldham, 1880). It was a debris avalanche characterised by "bursting of hill with upward and downward leap" and striking off the foundation of the Victoria Hotel and carrying it forward. The enormous volume of debris wiped out a part of the township including the pristine temple of Naina Devi, then located close to where today Boat House Club stands. The debris avalanche killed 143 people and converted the North-Western part of the lake into a level tract now known as 'Flat' (Fig. 1). The concave spoon-shaped slope spanned by the rope way is the scar of that landslide made up of 30-50 SW-dipping highly jointed states (Valdiya, 1988).

Other notable land slides occurred within the basin during 1939, 1942 and 1958. On July 31, 1939, the middle Ayarpatta was breached over a tract of 30 m in length and 90 m in height. A minor slip occurred in July 1942 below Edwinstone cottage. The shattered blocks of dolomites and quartzites often slip down from the precipitous slope to Phansi Gadhera.

3.2 Factors Affecting Lake Life

Practically, the life of a lake may be affected in two ways. In first case, the lake storage capacity may be reduced to the minimum possible due to sedimentation. In second case, the lake may be polluted due to the entry of various pollutants, upto an extent that it may not meet the water quality standards, thus rendering the lake unusable. This study addresses only the first problem.

In case of Lake Nainital, two main processes - (i) sheetwash & gully erosion and (ii) frequent landslide events producing huge amount of sediment and loose detritus material - have filled up the lake to a larger extent. Almost half of the areal extent of the lake basin is covered with debris generated by mass-movements in past.

Incised channels, barren land and the 23 delta fans growing at the banks of lake, indicate that the sheetwash and gully erosion have been aggravated due to increased anthropogenic activities and probable neotectonic activities in the lake catchment. However, the delta fans are partly removed every year by the NLSADA.

3.3 Previous Work

On the basis of PWD lake sounding data, various investigators have studied, in part, the rate of sedimentation using conventional techniques.

The first attempt was made by Hukku of GSI to study the rate of sedimentation in Nainital lake on the basis of the sounding data supplied by the PWD authorities for the years

1945 to 1965. The results of these studies were discussed in the Hill Slide Safety Committee meeting held on 21st Nov. 1966, when the anomalies were reported in the lake sounding data. Later, the PWD authorities scrutinised the data and the verified data for the years 1960 to 1966 were provided to Hukku for estimating the rate of sedimentation in the lake. On the basis of these data, Hukku et al (1968) reported the Average rate of silting equal to 62576.49 m^3/yr (22,09,621.57 cubic ft or 50.72 acre ft. per year) for a catchment of 1.92 sq. miles of Nainital lake. It gives a rate of sedimentation of about 26.41 acre ft per sq. mile or 8561.87 m^3/sq.km of the catchment per year which is very high. Hukku et al indicated the rate of silting about 22 lakh cubic ft (62576 m^3) per year and the life of the lake, at this rate was predicted to about 82 years. However, while comparing the lake floor sounding carried out by Ball (1878) with the PWD sounding data collected in 1965, he estimated that the lake will be completely filled up in 490 years. Hukku pointed out that even with the revised data made available by the PWD for the period 1960-1966 , the computation revealed scouring of the lake bed during the years 1960-61 and 1964-65 instead of sediment accumulation which indicated that the data made available to him was still doubtful about its validity.

Hukku et al (1968) further reported that the rate of sedimentation as calculated above was also found inconsistent with the rate of silting calculated on the basis of Khosla formula (16 acre ft. or 19736 m^3), Joglekar formula (17.2 acre ft or 21216.2 m) and by the formula of Krishnaswamy et al (8 acre ft. or 6167.5 m). The life of Nainital lake has been predicted 350 years, using Khosla and Joglekar formulae, which are normally used for the calculation of rate of sediment deposited in man made lakes (reservoirs), while it comes around 700 years, if calculated using Krishnaswamy's empirical formula.

Rawat (1987) predicted the lake life about 380 years based on 1969 and 1979 bathymetric data. He also calculated the rate of silting between the years 1865 and 1969 as 63.93 m^3/year. However, this rate increased to 77.64 m^3/year between 1969 and 1979, as reported by Rawat, which probably is the result of increased human activities in the lake catchment. Sharma, (1987) found the rate of sediment deposition as 0.021 million cubic metres per year. He considered 6.99 million cubic metres (PWD, Nainital) lake volume and indicated that lake will be filled up in 314.52 years.

Das et al (1993) made an attempt to determine the sedimentation rate by using the Pb-210 and Ra-226 in Nainital lake. Das collected three sample cores from different locations near to the offshore of lake. On the basis of the cores, he reported the rate of sedimentation as 11.5 mm/yr in the Nainital lake.

3.3.1 Data collection

Continuous monitoring of lake floor has been carried out by PWD, Nainital since 1947 using conventional sounding technique. The lake sounding data have been collected for the years 1947 to 1993 (except 1978 to 1988) from PWD, Nainital. The PWD Nainital carries the lake sounding once in a year, mainly in the months of November and December.

4.0 ESTIMATION OF SEDIMENTATION RATE

4.1 Using Conventional Methods

4.1.1 Sounding method

The annual sounding data collected from PWD office, Nainital have been statistically analysed for calculating the amount of sediments deposited during different time periods i. e.,1960-1965, 1965-1970, 1970-1975, 1972-1973, 1960-1975, 1985-1996, 1990-1993 and 1990-1996. The data have been presented in the Table 1 to 8.

The analysis reveals that 0.198 million cubic metres of sediment have been deposited in the lake during 1960-1965, at the rate of 0.0396 million cubic metres per year. Similarly, 0.567 million cubic meters of sediment deposited during 1965-1970, at the rate of 0.113 million cubic per year. Sedimentation rates obtained during other selected years are presented in Table 9.

Table 1: Details of sediment deposited along different section line during 1960 - 1965.

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1960	1965	Diff.	1960	1965	Diff.	1960	1965	Diff.	1960	1965	Diff.	1960	1965	Diff.
30.48	12.12	11.57	+0.55	19.13	18.29	-0.84	13.05	13.41	-0.36	12.44	13.11	-0.67	9.39	8.84	+0.55
60.96	13.95	14.46	-0.51	22.18	22.25	-0.07	17.92	17.98	-0.06	20.05	20.42	-0.37	20.67	19.51	+1.16
91.44	16.09	15.53	+0.56	22.18	22.55	-0.37	18.23	17.68	+0.55	21.58	21.64	-0.06	22.80	21.94	+0.86
121.92	15.17	15.83	-0.66	23.10	23.16	-0.06	18.53	18.29	+0.24	23.41	21.94	+1.47	23.41	22.55	+0.86
152.40	17.92	18.27	-0.35	22.79	23.47	-0.68	17.92	13.11	+4.81	25.85	25.30	+0.55	22.81	22.55	+0.25
182.88	17.92	17.36	+0.56	23.40	23.77	-0.37	11.22	12.19	-0.97	21.58	22.55	-0.97	24.33	22.25	+2.08
213.36	15.48	14.62	+0.86	21.88	23.47	-1.59	9.39	9.75	-0.36	22.80	22.25	+0.55	24.63	22.25	+2.38
243.84	13.65	12.48	+1.17	22.18	20.42	+1.76	11.83	12.19	-0.36	23.41	24.69	-1.28	23.41	22.86	+0.55
274.52	11.82	11.87	-0.05	6.33	10.06	+1.76	18.53	17.37	+1.16	25.85	24.99	+0.86	20.98	15.54	+5.44
304.80	9.38	7.60	+1.78	-	6.40	-0.07	20.05	20.12	-0.07	27.37	24.99	+2.38	13.05	12.80	+0.25
335.28	4.81	3.64	+1.17	-	-	-	-	-	-	18.53	18.59	-0.06	5.73	6.00	-0.27
365.76	-	-	-		-	-	-	-	-	16.70	17.07	-0.37	-	-	-
Sediment deposited along section line			+5.07			-0.53			+4.58			+2.03			+14.11
Mean Silting			+0.46			-0.05			+0.46			+0.17			+1.28

- Indicates Scouring

+ Indicates Silting

Table 2: Details of sediment deposited along different section line during 1965 - 1970.

Observation point along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1965	1970	Diff.	1965	1970	Diff.	1965	1970	Diff.	1965	1970	Diff.	1965	1970	Diff.
30.48	11.57	10.72	+0.85	18.29	14.58	+3.71	13.41	9.47	+3.94	13.13	12.47	+0.66	8.85	7.23	+1.62
60.96	14.46	13.47	+0.99	22.25	21.47	+0.78	17.98	17.47	+0.51	20.42	19.47	+0.97	19.52	18.73	+0.79
91.44	15.33	14.62	+0.71	22.55	23.97	-1.42	17.68	17.22	+0.46	21.66	18.71	+2.95	21.96	20.99	+0.97
121.92	15.83	14.22	+1.61	23.16	24.22	-1.06	18.29	13.22	+5.07	21.96	20.62	+1.34	22.57	21.74	+0.83
152.40	18.27	13.83	+4.44	23.47	24.22	-0.75	13.11	10.62	+2.49	25.31	20.22	+5.09	22.51	21.24	+1.27
182.88	17.37	14.58	+2.79	23.77	22.47	+1.30	12.19	8.71	+3.48	22.57	22.22	+0.35	22.27	21.47	+0.53
213.36	14.62	14.72	-0.10	23.47	23.96	-0.49	9.75	6.71	+3.04	22.26	23.22	-0.96	22.27	20.49	+1.78
243.84	12.48	10.97	+1.51	20.42	23.47	-3.05	12.19	9.47	+2.72	24.70	24.97	0.27	22.88	19.24	+3.64
274.52	11.87	9.22	+2.65	10.06	8.97	+1.09	17.37	18.71	-1.34	25.01	23.47	+1.54	15.56	14.23	+1.33
304.80	7.60	6.97	+0.63	6.40	-		20.12	19.22	+0.90	25.01	22.97	+2.04	12.82	7.99	+4.83
335.28	3.64	-								18.61	19.22	-0.61			
365.76															
Sediment deposited along section line			+ 16.08			+0.11			+ 21.27			+ 18.21			+17.59
Mean Silting			+1.60			+0.01			+2.13			+1.66			+1.76

- Indicates Scouring

+ Indicates Silting

Table 3: Details of sediment deposited along different section line during 1970 - 1975.

Observation p488	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
Sect. Line	1970	1975	Diff.	1970	1975	Diff.	1970	1975	Diff.8X1970		1975	Diff.	1970	1975	Diff.
30.48	10.72	11.77	-1.05	14.58	17.56	-2.98	9.47	12.69	-3.22	12.47	14.53	-2.06	7.23	7.24	-0.01
60.96	13.47	14.20	-0.73	21.47	21.82	-0.35	17.47	17.57	-0.10	19.47	20.01	-0.54	18.73	20.65	-1.92
91.44	14.62	15.12	-0.50	23.97	23.04	+0.93	17.22	15.74	+1.48	18.71	20.92	-2.21	20.99	22.17	-1.18
121.92	14.22	14.81	-0.59	24.22	23.65	+0.57	13.22	15.74	-2.52	20.62	21.23	-0.61	21.74	22.78	-1.04
152.40	13.83	16.64	-2.81	24.22	23.65	+0.57	10.62	10.87	-0.25	20.22	22.75	-2.53	20.49	22.78	-1.54
182.88	14.58	18.17	-3.59	22.47	23.35	-0.88	8.71	12.39	-3.68	22.22	22.75	-0.53	19.24	23.39	-1.65
213.36	14.72	16.03	-1.31	23.96	23.96	0	6.71	13.91	-5.20	23.22	23.36	-0.14	14.23	22.78	-2.29
243.84	10.97	12.68	-1.71	23.47	22.43	+0.04	9.47	11.84	-4.44	24.97	24.58	+0.39	7.99	21.87	-2.63
274.52	9.22	9.6[illegible]	-0.41	8.97	9.63	-0.66	18.71	17.88	+0.83	23.47	25.19	-1.72		19.43	-5.20
304.80	6.97	8.72	-1.75							22.97	24.58	-1.61		11.51	-3.52
335.28										19.22	23.67	-4.45			
365.76										11.97	15.13	-3.16			
Sediment deposited along section line			- 14.45			-2.76			- 17.58			- 19.17			- 20.98
Mean Silting			-1.44			-0.28			-1.95			-1.59			-2.10

- Indicates Scouring

\+ Indicates Silting

Table 4: Details of sediment deposited along different section line during 1972 - 1975.

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1972	1975	Diff.	1972	1975	Diff.	1972	1975	Diff.	1972	1975	Diff.	1972	1975	Diff.
30.48	12.35	11.77	+0.58	17.86	17.55	+0.31	12.37	12.73	-0.36	15.42	14.55	+0.87	7.19	7.24	-0.05
60.96	14.49	14.20	+0.29	22.42	21.82	+0.60	17.86	12.73	+5.13	20.30	20.04	+0.26	19.99	20.65	-0.66
91.44	16.93	15.12	+1.81	22.74	23.04	-0.30	18.47	17.60	+0.87	20.91	21.87	-0.96	22.13	22.17	-0.04
121.92	16.93	14.81	+2.12	23.04	23.65	-0.61	16.95	15.77	+1.18	20.91	22.17	-1.26	23.35	22.78	+0.57
152.40	17.54	16.64	+0.90	23.96	23.65	+0.31	12.37	10.90	+1.47	23.04	22.78	+0.26	23.65	22.78	+0.57
182.88	19.37	18.12	+1.25	24.26	23.35	+0.91	9.91	9.68	+0.23	22.74	22.78	-0.04	23.65	23.39	+0.26
213.36	18.17	16.03	+2.14	23.65	23.95	-0.30	21.52	13.94	+7.58	23.65	23.39	+0.26	23.96	22.78	+1.18
243.84	12.97	12.68	+0.29	22.13	22.43	-0.30	13.29	11.51	+1.78	23.65	24.61	-0.96	22.74	21.87	+0.87
274.52	11.14	9.63	+1.51	10.85	9.63	+1.22	12.38	17.91	-5.53	25.18	25.22	-0.04	19.99	19.43	+0.56
304.80	8.70	8.72	-0.02							25.48	24.61	+0.87	14.51	12.42	+2.09
335.28	3.52	3.84	-0.32							24.57	23.69	+0.88			
365.76										19.08	15.16	+3.92			
Sediment deposited along section line			+ 10.55			+1.84			+ 12.35			+4.06			+5.35
Mean Silting			+0.96			+0.20			+1.37			+0.34			+0.54

- Indicates Scouring

\+ Indicates Silting

Table 5: Details of sediment deposited along different section line during 1983 - 1990.

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1990	1983	Diff.	1990	1993	Diff.	1990	1993	Diff.	1990	1993	Diff.	1990	1993	Diff.
30.48	11.85	12.00	-0.15	20.65	15.70	+4.95	16.25	13.60	+2.65	15.90	13.40	+2.40	15.35	14.85	+0.50
60.96	14.95	13.25	+1.70	23.55	21.20	+2.35	18.95	16.40	+2.55	21.05	18.60	+2.45	21.05	18.20	+2.85
91.44	16.65	14.30	+2.35	24.25	22.90	+1.35	17.45	17.00	+0.45	21.75	19.30	+2.45	22.85	20.90	+1.95
121.92	17.95	14.50	+3.45	24.50	23.00	+1.50	12.55	13.30	-0.75	21.45	19.80	+1.65	23.65	22.00	+1.65
152.40	19.85	15.50	+4.35	24.60	19.30	+5.30	10.65	10.00	+0.65	21.50	21.20	+0.30	23.85	22.00	+1.85
182.88	18.20	17.40	+0.80	23.35	22.50	+0.85	8.20	8.80	-0.60	23.85	20.70	+3.15	23.45	22.10	+1.35
213.36	17.05	17.20	-0.15	24.65	22.25	+2.40	7.85	7.10	+0.75	24.55	23.45	+1.10	22.95	21.20	+1.75
243.84	13.55	14.10	-0.55	24.05	22.70	+1.35	11.45	8.40	+3.05	26.05	23.60	+2.45	21.65	19.80	+1.85
274.52	10.80	13.70	-2.90	12.05	16.50	-4.45	21.80	15.70	+6.10	26.25	23.60	+2.65	17.85	16.60	+1.25
304.80	9.05	11.95	-2.90				20.00	20.40	-0.40	25.85	23.60	+2.25			
335 28	6.05	6.90	-0.85							24.05	20.20	+3.85			
365.76	-	-								15.85	11.60	+4.25			
Sediment deposited along section line			+5.15			+ 15.60			+ 14.45			+ 28.95			+ 15.00
Mean Silting			+0.47			+1.73			+1.45			+2.41			+1.67

- Indicates Scouring

+ Indicates Silting

Table 6: Details of sediment deposited along different section line during different period

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1990	1996	Diff.	1990	1996	Diff.	1990	1996	Diff.	1990	1996	Diff.	1990	1996	Diff.
30	12.32	12.67	-0.35	21.12	19.07	+2.05	16.72	10.08	+6.64	16.37	14.48	+1.69	21.52	19.38	+2.14
60	15.42	14.37	+1.05	24.12	22.32	+1.82	19.42	17.48	+1.94	21.52	20.08	+1.44	23.32	22.08	+1.24
90	17.12	16.07	+1.05	24.72	23.42	+1.30	17.92	18.08	-0.16	22.22	20.28	+1.94	24.12	22.68	+1.44
120	18.42	16.52	+1.90	24.97	23.77	+1.20	13.02	13.38	-0.36	21.92	21.08	+0.84	24.32	23.08	+1.24
150	19.42	18.47	+0.95	25.07	24.07	+1.00	11.12	10.38	+0.74	21.97	22.58	-0.61	23.92	22.58	+1.34
180	19.67	18.87	-0.80	23.82	23.97	-0.15	8.67	10.28	-1.61	24.32	25.08	-0.76	23.42	23.23	+0.19
210	17.52	17.87	-0.35	25.12	23.97	+1.15	8.32	8.28	-0.04	25.02	23.38	+1.64	22.12	22.48	-0.36
240	14.02	14.87	-0.85	24.52	23.47	+1.05	11.92	12.78	-0.86	26.52	23.88	+2.64	18.32	19.98	-1.66
270	11.27	11.87	-0.60				22.27	21.28	+0.99	26.72	23.98	+2.74			
300	9.52	10.07	-0.55				20.47	19.63	+0.79	26.32	23.28				
330										24.52	24.98	-0.46			
360										16.32	19.08	-2.76			
Sediment deposited along section line			+3.05			+9.42			+8.07			+12.60			+5.57
Mean Silting			+0.31			+1.18			+0.81			+1.05			+0.70

\- Indicates Scouring

\+ Indicates Silting

Table 7: Details of sediment deposited along different section line during 1960 - 1975

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line · 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1960	1975	Diff.	1960	1975	Diff.	1960	1975	Diff.	1960	1975	Diff.	1960	1975	Diff.
30.48	12.12	11.77	+0.35	19.13	17.55	+1.58	13.05	12.73	+0.32	12.44	14.55	-2.11	9.39	7.24	+2.15
60.96	13.95	14.2	-0.25	22.18	21.82	+0.36	17.92	12.73	+5.19	20.05	20.04	+0.01	20.67	20.65	+0.02
91.44	16.09	15.12	+0.97	22.18	23.04	-0.86	18.23	17.60	+0.63	21.58	21.87	-0.29	22.80	22.17	+0.63
121,92	15.17	14.81	+0.36	23.10	23.65	-0.55	18.53	15.77	+2.76	23.41	22.17	+1.24	23.41	22.78	+0.63
152.40	17.92	16.64	+1.28	22.79	23.65	-0.86	17.92	10.90	+7.02	25.85	22.78	+3.07	22,80	22.78	+0.02
182.88	17.92	18.17	-0.25	23.40	23.35	+0.05	11.22	9.68	+1.54	21.58	22.78	-1.20	24.33	23.39	+0.94
213.36	15.48	16.03	-0.55	21.88	23.96	-2.08	9.39	13.94	-4.55	22.80	23.39	-0.59	24.63	22.78	+1.85
243.84	13.65	12.68	+0 97	22.18	22.43	-0.25	11.83	11.51	+0.32	23.41	24.61	-1.20	23.41	21.87	+1.54
274.52	11.82	9.63	+2.19	11.82	9.63	+2.19	18.53	17.91	+0.62	25.85	25.22	+0.63	20.98	19.43	+1.55
304.80	9.38	8.72	+0.66	6.33	4.75	+1.58	20.05			27.37	24.61	+2.76	13.05	12.42	+0.63
335.28										18.53	23.70	-5.17			
365.76										16.70	15.16	+1.54			
Sediment deposited along section line			+5.73			+1.16			+ 13.85			-1.31			+9.96
Mean Silting			+0.57			+0.12			+1.54			-0.11			+0.99

- Indicates Scouring

+ Indicates Silting

Table 8: Details of sediment deposited along different section line during 1985 - 1996.

Observation points along Sect. Line	Section Line - 1 (Depth in Meters)			Section Line - 4 (Depth in Meters)			Section Line - 6 (Depth in Meters)			Section Line - 7 (Depth in Meters)			Section Line - 10 (Depth in Meters)		
	1985	1996	Diff.	1985	1996	Diff.	1985	1996	Diff.	1985	1996	Diff.	1985	1996	Diff.
30	12.00	12.67	-0.67	20.02	19.07	+0.95	9.32	10.08	-0.76	14.82	14.68	+0.14	7.83	5.08	+2.75
60	14.40	14.37	+0.03	23.82	22.32	+1.50	18.32	17.48	+0.84	21.12	20.08	+1.04	20.23	19.38	+0.85
90	16.10	16.07	+0.03	23.82	23.42	+0.40	18.52	18.08	+0.44	22.32	20.28	+2.04	23.03	22.08	+0.95
120	16.30	16.52	-0.22	25.97	23.77	+2.20	11.22	13.38	-2.16	23.82	21.08	+2.74	24.03	22.68	+1.35
150	18,30	18.47	-0.17	25.17	24.07	-1.90	13.12	10.38	+2.74	24.22	22.58	+1.64	23.63	23.08	+0.55
180	18.70	18.87	-0.17	24.22	23.97	+0.25	9.02	10.28	-1.26	28.32	25.08	+3.24	23.93	22.58	+1.35
210	18.00	17.87	+0.13	25.12	23.97	+1.15	7.82	8.28	-0.46	25.72	23.38	+2.34	22.73	23.23	-0.50
240	14.60	14.87	-0.27	24.22	23.47	+0.75	12.02	12,78	-0.76	24.02	23.88	+0.14	21.43	24.48	-1.05
270	11.30	11,87	-0.57				21.62	21.28	+0.34	27.02	23.98	+3.04	17.73	19.98	-2.25
300	9.95	10.07	-0.12				19.02	19.68	-0.66	27.12	23.28	+3.84			
330										25.02	24.98	+0.54			
360										17.92	19.08	-1.16			
Sediment deposited along section line			-2.00			+5.30			-1.70			+ 19.58			+4.00
Mean Silting			-0.20			+0.66			-0.17			+1.63			+0 44

\- Indicates Scouring

\+ Indicates Silting

Table 9: Total sediment accumulation along different section in Nainital Lake during different time periods.

Selected Years	Sections	Average Sedimentation Meters	Area in Section in Sq./meters	Sedimentation m^3	Total Sedimentation m^3	Sedimentation in m^3/yr
1960-1965	0-1	+0.23	50103.75	11523.86	192193.41	38438.68
	1-4	+0.22	121208.29	25453.74		
	4-6	+0.21	64622.29	13570.68		
	6-7	+0.32	35649.51	11407.84		
	7-10	+0.73	154653.97	112897.39		
	10-0	+0.64	27093.60	17339.9		
1965-1970	0-1	+0.82	50103.75	40083.00	565866.46	113173.29
	1-4	+0.83	121208.29	100602.88		
	4-6	+1.07	64622.29	69145.85		
	6-7	+1.90	35649.51	67734.07		
	7-10	+1.71	154653.97	264458.29		
	10-0	+0.88	27093.60	23842.37		
1970-1975	0-1	-0.72	50103.75	-36074.70	-591228.16	Results indicating only scouring during this selected period.
	1-4	-0.88	121208.29	-106663.29		
	4-6	-1.12	64622.29	-72376.96		
	6-7	-1.77	35649.51	-63099.63		
	7-10	-1.84	154653.97	-284563.30		
	10-0	-1.05	27093.60	-28448.28		
1972-1975	0-1	+0.48	50103.75	24049.80	251423.81	83807.94
	1-4	+0.58	121208.29	70300.80		
	4-6	+0.79	64622.29	51051.61		
	6-7	+0.86	35649.51	30658.58		
	7-10	+0.44	154653.97	68047.75		
	10-0	+0.27	27093.60	7315.27		
1960-1975	0-1	+0.29	50103.75	14530.08	216283.03	14418.87
	1-4	+0.34	121208.29	41210.80		
	4-7	+0.84	64622.29	53636.50		
	6-7	+0.71	35649.51	25311.15		
	7-10	+0.44	154653.97	68047.70		
	10-0	+0.55	27093.60	13546.80		
1985-1996	0-1	-0.10	50103.75	5010.38	236858.34	21532.57
	1-4	+0.23	121208.29	27877.91		
	4-7	+0.25	64622.29	16155.57		
	6-7	+0.73	35649.51	26024.14		
	7-10	+1.04	154653.97	160840.13		
	10-0	+0.22	27093.60	5960.59		
1990-1993	0-1	+0.24	50103.75	12024.98	655159.73	218386.58
	1-4	+1.10	121208.29	133329.12		
	4-7	+1.59	64622.29	102749.44		
	6-7	+1.93	35649.51	68803.55		
	7-10	+2.04	154653.97	315494.10		
	10-0	+0.84	27093.60	22758.62		
1990-1996	0-1	+0.16	50103.75	8016.60	341631.18	56938.53
	1-4	+0.75	121208.29	90906.22		
	4-7	+0.99	64622.29	63976.07		
	6-7	+0.93	35649.51	33154.04		
	7-10	+0.88	154653.97	136095.49		
	10-0	+0.35	27093.60	9482.76		

The analysis of data during 1972-73 reveals that 0.253 million cubic meter sediments was deposited at the rate of cubic million 0.0845 meters per year, while after the fifteen years during 1990-1993, data indicates that huge deposition of sediment has taken place at the rate of 0.0218 million cubic meters per year. But, the data of lake sounding for the years 1970-1975, gives an indication that no deposition has taken palace during these years which may not be true. The rate of scouring has been observed during these years at the rate of 0.0118 million cubic meters per year. This scouring of lake bed during the 1970-1975 instead of silting, creates suspicion about the validity of lake sounding data. The similar doubts have been raised about the validity of lake sounding data by Hukku et al (1968). However, in the present case, this fact is almost confirmed as the high deposition rates have been found during the years 1972-1975.

If one ignores the data of 1970-75 and compares the rate of deposition of sediments, the rate of deposition is 2.9 times higher in 1965-1970 than that of 1960-1965, 2.2 times higher in 1972-1975 (an intermediate period between 1970-1975) than that of 1960-1965 and 5.6 times higher in 1990-1993 than that of 1960-1965. It implies the considerable increase in the rate of deposition of sediment and indicates that the anthropogenic activities have accelerated the rate of deposition about 5 times than that of 1960-1965 rate. The sounding data of 1960-1965, 1965-1970 and 1972 also reveal that the deposition of sediment is maximum in the section lines 1, 6 and 10. The minimum sedimentation along in the section lines 4 and 7 is associated with morphological constructions or under water ridge along section line 6. Bottom current flowing over section lines 4 and 7 sweep the material immediately from the sides of the above section. It has been interpreted that the larger scouring along the above mentioned part may be high during heavy rain when strong bottom currents and high surface currents are generated.

During the period of 1990-1993 , remarkable change has occurred which reveals that minimum deposition has been taken place along the section lines 1, 4 and 7 in comparison to the earlier years. It implies that the major changes have occurred in the under water topography of lake and direction of bottom current flow which has changed the earlier pattern of sediment deposition.

4.1.2 Sediment balance method

Sediment inflow to the lake has been monitored at the two major inflow points to the lake. The variation in Suspended Sediment (SS) concentration in the inflow with time is shown in Fig. 3. 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 suspended 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). This gives a sedimentation deposition in the lake at the rate of 0.69 cm/yr. The detailed sediment balance has been presented in the following Table:

Table 10: Rate of sediment accumulation estimated by sediment balance method

	Suspended Sediment Concentration	Total Susp. 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)

4.2 Pb-210 Method for Sediment Dating

Over the past twenty years, ^{210}Pb dating has developed into a major tool for paleolimnologists, historians, geographers and environmental scientists. Many coring techniques are available, ranging from the simple to the quite complex, but all have been shown to give good results. The analytical methods for ^{210}Pb and ^{226}Ra are well established

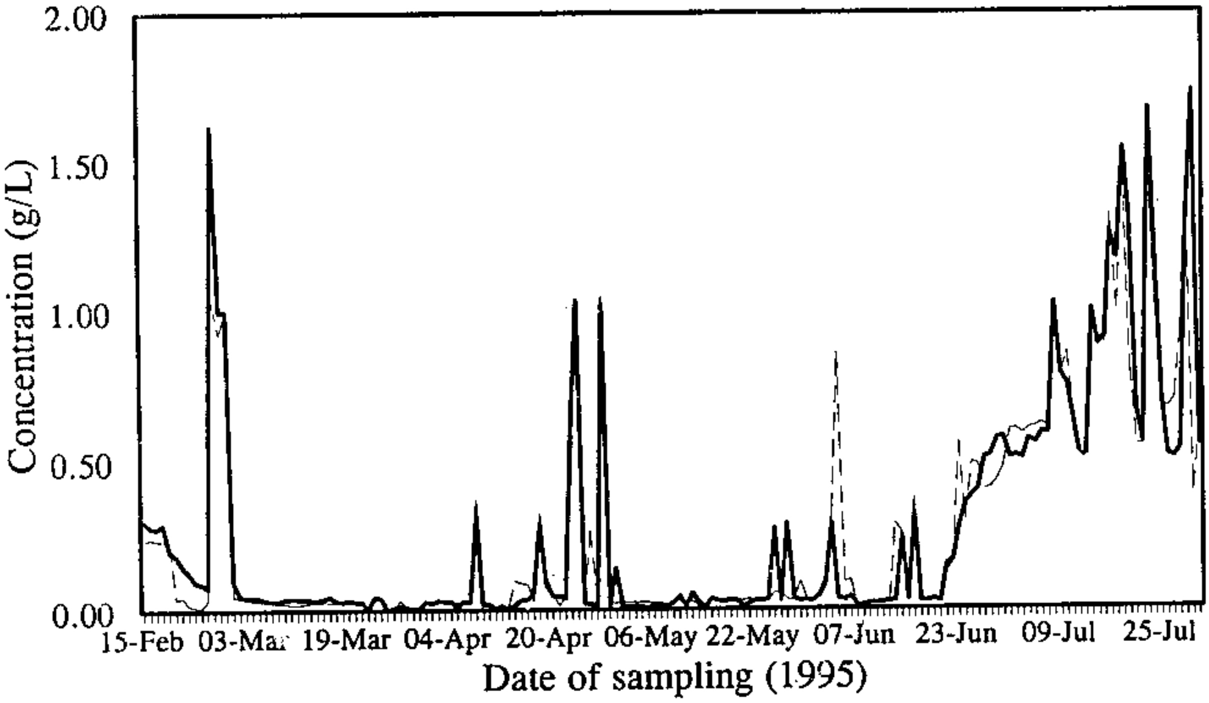

Fig. 3. Variation of suspended sediment concentration with time in nalahs draining into the lake Nainital.

and of sufficient variety that they can be carried out by a competent analyst in any reasonably equipped laboratory.

Two main approaches to the interpretation of ^{210}Pb sediment profiles are currently in use, the constant initial concentration (CIC) model and the constant rate of supply (CRS) model. These often yield similar chronologies for the more recent sediments, but there is sometimes divergence in the time scales relating to deeper deposits. There are no definitive criteria for choosing one model in preference to another. Each sediment profile should be considered in relation to all available data, to other chronologies and, wherever possible, to other sediment cores taken from the same water body.

The applications of ^{210}Pb dating are many and varied. A sediment core records a detailed history of the environment in its vicinity and the ^{210}Pb dating technique provides a chronology covering a time scale of 100-150 years, uniquely suited to the period of man's greatest impact.

4.2.1 Analytical techniques

^{210}Pb dating depends on the accurate determination of the level of unsupported ^{210}Pb in a series of sediment samples. In order to do this, the total ^{210}Pb content of each sample is determined initially. The supported ^{210}Pb is then measured by analysis for its precursor and ^{226}Ra and the unsupported ^{210}Pb derived by subtraction of this value from the total ^{210}Pb. Ideally, all sections of a sediment core should be analysed for ^{210}Pb and ^{226}Ra until a depth is reached at which the total ^{210}Pb is indistinguishable from the supported ^{210}Pb. However, for economic reasons this is not nonnally done and it is usual to determine ^{210}Pb in about 10 sections between the surface and the region where the unsupported ^{210}Pb is no longer detectable. If the ^{226}Ra content is relatively constant, then it is generally sufficient to analyse sections at the top, middle and bottom of the region of interest to establish the supported ^{210}Pb. If the ^{226}Ra is variable however, then all sections analysed for ^{210}Pb must also be analysed for ^{226}Ra.

4.2.2 Determination of ^{210}Pb activity

The direct measurement of ^{210}Pb in sediment by detection of its 47 KeV photon emission has been reported by Gäggeler et.al.(1976) and Bergerioux et.al. (1980). This method has the advantage of being non-destructive and the sediment is therefore available for other measurements. However the 47 KeV emission from ^{210}Pb is only present in 4 per cent of its disintegrations and the method is relatively insensitive. The limit of detection is about 2 pCi g^{-1} for a sample of about 100 g, which seriously limits its application to many cores where the concentration of ^{210}Pb, even in the surface sediments, may be less than 5 pCi g^{-1}. In some core sections, the weight of sediment available for analysis is only a few grams and this will further increase the limit of detection. However the method may well have application in determining the total ^{210}Pb in a core where no profiling is required. In this case the whole core could be homogenised before a sufficiently large sample was taken for measurement.

Because of the low energy of its beta emission ^{210}Pb is often determined by means of its ^{210}Bi daughter. This has a half-life of 5 days and emits a beta particle with E_{max}1.16 MeV. A technique used by many workers [Krishnaswamy et al (1971), Petit, D. (1974) and Koide, M. et al (1973)] for determining ^{210}Pb in sediment is as follows. A sample of dried sediment is leached with hydrochloric acid and then the ^{210}Pb along with the added lead carrier is removed from the resultant solution by anion exchange. The lead is then precipitated, either as sulphate or chromate, and a suitable source prepared for beta counting. The chemical recovery is determined gravimetrically and the source is left for about 5 weeks before counting to allow the ^{210}Bi to equilibrate with its parent ^{210}Pb.

An alternative procedure is to determine the ^{210}Po grand-daughter of ^{210}Pb. This has a half-life of 138 days and decays to stable ^{206}Pb, emitting an alpha particle of 5.3 MeV. As deposition rates are generally less than 1 cm y^{-1}, the ^{210}Po will be in equilibrium with ^{210}Pb in all but the surface layer. A number of workers have adopted this approach, including Robbins and Edgington (1975), Krishnaswamy et al. (1980) and Benninger et al. (1979). The basic radiochemical procedure is to add ^{208}Po as a yield tracer, we oxidise or leach the sediment sample with strong mineral acids, filter off residual solids and convert the solution to one of dilute hydrochloric acid. Polonium nuclides are then spontaneously deposited on silver discs prior to counting by alpha spectrometry. Eakins and Morrison (1978) employed a different procedure, in which ^{210}Po is dry distilled from the sediment as the volatile tetrachloride prior to deposition on silver, a technique which has also been employed by El-Daoushy (1978). There are a number of advantages in determining ^{210}Pb via ^{210}Po. Alpha counting is inherently more sensitive than beta counting and the ^{210}Po can be identified unequivocally. There is no need of any delay between preparation of the source and counting, and the separation of ^{210}Po from sediments is relatively simple.

Another technique for determining ^{210}Pb has been described by Jensen et al. (1977), in which ^{210}Pb is extracted from a sample of ashed sediment with nitric acid and electrodeposited on platinum. After allowing for ingrowth, ^{210}Po is detected by alpha track counting using a plastic detector. This method is very sensitive but lacks the specificity of alpha spectrometry.

4.2.3 Determination of ^{226}Ra activity

There are a number of approaches to determine of ^{226}Ra in sediments. If the concentration is fairly high and the sample is large, ^{226}Ra can be determined directly by gamma counting of its decay products. ^{226}Ra is first obtained from the sediment either by acid leaching or fusion and subsequent dissolution. The solution is stored in a closed system to allow ingrowth of ^{222}Rn, which is then flushed out with an inert gas into a scintillation cell. The cell is stored for a few hours before being coupled to a photomultiplier tube and then counted.

There are different procedures for producing a solid source for alpha counting depending upon the upon the obtaining of a solution of ^{226}Ra from the sediment. ^{226}Ra is then separated from impurities by a variety of methods before a source is prepared for alpha counting. Koide and Bruland (1975) used ^{226}Ra as a yield tracer, coprecipitating the radium with lead nitrate. The lead was then removed by anion exchange and the radium further purified by cation exchange. The purified radium was electrodeposited from a 2-propanol electrolyte onto a platinum disc prior to alpha spectrometry. Pennington et al. (1976)

coprecipitated ^{226}Ra with lead sulphate and subsequently with barium sulphate in the presence of ethylene diamine tetra-acetic acid. The barium sulphate was purified by reprecipitation and its alpha activity determined after storing to allow ingrowth of the ^{226}Ra daughter activities.

The chemical recovery was determining using ^{133}Ba as a gamma yield tracer. Joshi and Durham (1978) coprecipitated ^{226}Ra with lead and barium carriers from strong nitric acid and then separated the barium and ^{226}Ra from lead by ion exchange. The ^{226}Ra was subsequently coprecipitated with barium chromate which was stored prior to alpha counting.

4.2.4 Interpretation of ^{210}Pb profiles

The interpretation of a ^{210}Pb sediment profile and its conversion into one of life versus depth depends on assumptions concerning the supply of ^{210}Pb to the sediment column and its behaviour within it. It is generally assumed that the supply of atmospheric ^{210}Pb to the water surface and the catchment is constant on a time scale of 100-200 years. The flux may vary on time scales of the order of a year (39) but, as sediment sections taken for analysis normally span several years of accumulation, these short-term variations will be smoothed out. It is also assumed that there is no migration or diffusion of ^{210}Pb within the sediment column through the pore water. There is indirect evidence that migration is minimal from the fact that in some profiles there are sharp peaks and inflexions which would be smoothed if migration was significant. Similarly, it is assumed in determining the supported ^{210}Pb that both ^{210}Pb and ^{226}Ra (which is actually measured) are in equilibrium. This has been confirmed from the determination of ^{210}Pb and ^{226}Ra in the lower sections of over a hundred cores where the unsupported ^{210}Pb is no longer detectable. However, Imboden and Stiller (1982) have discussed the influence of ^{222}Rn diffusion on the ^{210}Pb distribution in sediments and have produced a mathematical model to describe the distribution of ^{222}Rn within a core. They believe that in cores having a low unsupported ^{210}Pb content, the assumption that ^{226}Ra and ^{210}Pb are in secular equilibrium should be treated with caution. There may well be a small disequilibrium between ^{210}Pb and ^{226}Ra near the sediment- water interface but, if the unsupported ^{210}Pb is in considerable excess, the effect on dating will be negligible.

4.2.5 Models used for ^{210}Pb profiles interpretation

The interpretation of a ^{210}Pb sediment profile and its conversion into one of life versus depth depends on assumptions concerning the supply of ^{210}Pb to the sediment column and its behaviour within the column. It is generally assumed that the supply of atmospheric ^{210}Pb to the water surface and the catchment is constant on a time scale of 100-200 years. The flux may vary on time scales of the order of a year but, as sediment sections taken for analysis normally span several years of accumulation, these short-term variations will be smoothed out. Based on the assumptions made and as well as the suitability of the models to the water body being studied any one of the model can be selected for interpreting the environmental isotope profile.

4.2.6 Constant initial concentration (CIC) model

The ^{210}Pb dating technique was first applied to lake sediments by Krishnaswamy et al. (1971) and to marine sediments by Koide et al. (1973). These and many other workers found that a semilogarithmic plot of the total ^{210}Pb concentration per unit weight of sediment against depth showed a roughly monotonic decline until a region of unchanging concentration was reached. The region of unchanging concentration is the supported ^{210}Pb maintained by ^{226}Ra within the sediment. Subtraction of the supported ^{210}Pb component from the profile results in the lower curve, which is a plot of the unsupported ^{210}Pb against depth. The unsupported ^{210}Pb decreases exponentially and the slope of the line represents a mean sedimentation rate. By a comparison of the concentration at any depth with that at the surface, the life of the sediment at that depth can be calculated from the equation for radioactive decay, which in this case can be expressed as:-

$$C_d = C_0 e^{-\lambda t} \qquad (1)$$

where C_d = concentration of ^{210}Pb at depth d

C_0 = concentration of ^{210}Pb at the surface

λ = decay constant for ^{210}Pb (0.031) t = life of sediment at depth d.

This model assumes that, over the time scale being studied, the concentration of ^{210}Pb in sediment at the mud/water interface has been constant. Because of this, it is often referred to as the constant initial concentration or CIC model. It has been validated for marine sediments by the analysis of varved cores from the Santa Barbara Basin (Koide et al., 1972).

In some profiles, a semilogarithmic plot of the unsupported ^{210}Pb concentration against depth is predominately linear, but the slope decreases near the surface. This is often simply the result of reduced compaction of near-surface sediments and the non-linearity is avoided by plotting the ^{210}Pb concentration against the cumulative dry mass of sediment. This technique has been adopted by many workers and has largely superseded the earlier procedure. Methods for assessing the effects of compaction on the calculation of sediment accumulation rates in the near-surface sediments of a core have been discussed by Wise (1977) and by Robbins and Edgington (1975).

Non-linearity in a ^{210}Pb profile near the surface of a core will also occur if the surface sediments are disturbed. The most common cause of sediment mixing is bioturbation, which normally affects only the top few cm of a core. The redistribution of surface sediments by deposit-feeding organisms has been investigated by Robbins et al. (1977) who found that beneath the zone of mixing, the unsupported ^{210}Pb profile in a core of constant sediment accumulation rate was linear. Bioturbation is normally less in freshwater sediments than those of marine origin, partly because of the small size of the freshwater benthos. Skei (1979), in a study of sediments in the Norwegian fjords, found that anoxic sediments were in general suitable for ^{210}Pb dating but that toxic sediments were often too disturbed by bioturbation.

A further source of non-linearity in a ^{210}Pb profile is a change in the accumulation rate. During the last 50-100 years, the sediment accumulation rate in many water bodies has increased, often due to eutrophication. One of two assumptions is implicit in the use of the CIC model to interpret such a profile:-

(1) There is a large excess of ^{210}Pb in solution in the overlying water and increased sedimentation merely entrains more of the excess. If the sediment has a limited capacity for ^{210}Pb this will result in its concentration remaining constant despite a change in accumulation rate.

(2) The main source of ^{210}Pb in sediment is material uniformly labelled with ^{210}Pb on the catchment and more of this is being transferred to the lake because of environmental change.

Pennington et al. (1976) used the CIC model to interpret non-linear ^{210}Pb profiles of a series of cores from Blelham Tarn. The ^{210}Pb chronology was consistent with both ^{137}Cs and paleomagnetic dating and gave similar ages for visible stratigraphic changes in sediments of different cores. However the use of the CIC model to interpret ^{210}Pb profiles where the sediment accumulation rate is changing does not always yield a chronology consistent with independent time scales and an alternative interpretation has been sought.

4.2.7 Constant rate of supply (CRS) or constant flux (CF) model

In equation (1) $C_0=F/R$ where F is the flux of unsupported ^{210}Pb to the sediment/water interface and R is the sediment accumulation rate. A change in the accumulation rate implies a change in either C_0 or F (or possibly both). The CIC model assumes that C_0 is constant but an alternative approach is to consider that F, the flux of unsupported ^{210}Pb to the sediment, is constant. This is termed the constant rate of supply or CRS model. It was first outlined by Goldberg (1963) and has since been developed by Appleby and Oldfield (1978). The constant flux assumption implies a constant residual of unsupported ^{210}Pb within the sediment column and the life t of sediments of depth d may be calculated from the radioactive decay law expressed as

$$A_d = A_0 e^{-\lambda t} \qquad (2)$$

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

$$r = \lambda A_d / C_d \qquad (3)$$

where C_d is the unsupported ^{210}Pb concentration. Oldfield et al. (1978) have used this model to reassess ^{210}Pb data for several lakes, and have obtained chronologies more consistent with independent dating methods than those obtained using the CIC model. Appleby et al. (1979) have validated the method in freshwater sediments by dating varved cores from Finland and Batterbee et al. (1980) have reassessed the ^{210}Pb chronology of Lake Växjösjön on the basis of a CRS model. The general effect of applying the CRS model is to assign greater ages to sediments at lower depths in a core, whereas there is often reasonable agreement between the chronologies for near-surface sediments. It should be noted that both the CIC and CRS models will give the same chronology if a semilogarithmic plot of unsupported ^{210}Pb against the cumulative dry mass of sediment is linear.

The other model can be a combination of both, i.e., constant initial concentration and constant flux or constant flux and constant rate of sediment (CFCS).

4.2.8 Selection of a model

Although the CRS model has led to a reassessment of many ^{210}Pb sediment profiles, it does not have universal application and it is not always clear which model should be used. Oldfield and Appleby (1983) have found empirically that, if the mean flux of unsupported ^{210}Pb to the sediment falls within the range expected from measured atmospheric fluxes (0.2-1.0 pCi $cm^{-2}y^{-1}$) the CRS model will give the more valid chronology but, where fluxes are much less than the atmospheric range, results have been poor. Oldfield and Appleby recommend analysis of more than one sediment core wherever possible, to indicate whether sediment resuspension and focusing are occurring. This will lead to reduced unsupported ^{210}Pb at sites where sediment erosion has taken place and enhanced deposits where focusing has occurred. In such cases, although the CRS model will not be valid for a single core, it may be valid for the lake bed as a whole.

Madsen and Sorensen (1979) recommend the use of a combination of CRS and CIC models in constructing a chronology. The CRS model is used for the near-surface sediments where the accumulation rate may be changing and the CIC model for the deeper sediments where it is constant.

If an horizon in a sediment core can be dated independently, for example by ^{137}Cs, pollen or magnetic measurements, or by an input from a known historical event such as ash from a forest fire or a volcano, then the model which gives the best fit to the independent chronology should be used.

4.2.9 Limitations and Uncertainties

In some circumstances it is impossible to date a sediment core by the ^{210}Pb technique, whichever model is used. A very high supported ^{210}Pb content can completely mask the unsupported ^{210}Pb derived from the atmosphere. Occasionally a sediment will have so little unsupported ^{210}Pb that it is difficult to distinguish it from a 'normal' supported ^{210}Pb content.

The reason for a very low unsupported ^{210}Pb content in sediment from a water body where there is no obvious sediment loss is not known, but it may be significant that it has only been observed in lakes with small catchment areas. This suggests that unsupported ^{210}Pb in a lake sediment may be derived predominately from the catchment. Perhaps the biggest uncertainty in ^{210}Pb dating is the extent to which the catchment contributes to the unsupported ^{210}Pb in sediment and this is an area which warrants further study.

A further area of uncertainty lies in the distribution of ^{210}Pb within the various components of sediment. According to Lewis (1977) ^{210}Pb in soils is sequestered by organic material and is concentrated in the organic layers and Mackereth (1966) considers that 90 percent of the organic matter in a sediment will have come from the catchment. Cooper et al. (1981) in a study of the speciation of radionuclides in sediments and soils found that over 30 per cent of the ^{210}Pb activity was bound to organic matter. There is therefore mounting evidence that ^{210}Pb is associated with organic material in sediments, but further work is required to confirm this.

4.3 Cs-137 Method for Sediment Dating

Cesium - 137 is produced in the atmosphere due to cosmic rays interactions in the atmosphere. However, its concentration increased many folds in the atmosphere due to the test of nuclear weapons and since 1954, it has been globally detectable Cs-137 is strongly absorbed on tine particles like clay materials, silts and humic materials. Surface soils with an adsorptive capacity will have a Cs-137 content and therefore be able to act as a self tracer. In a catchment, accumulation of a sediment layer in a lake is a measure of its trap efficiency. A comparison of Cs-137 of catchment soils with that of associated lake sediment shows a pronounced build up of the latter. The sedimentation rates can be calculated from the depths of two principal time horizons i.e. 1955 and 1964 , in the Cs-137 concentration profile. Presently this has been considered as more reliable technique for the dating of sedimentation rate in past 40 years.

4.3.1 Temporal variations in ^{137}Cs fallout

The principal sources of information on ^{137}Cs levels in fallout are the various reports of measurements from a global network of US and UK monitoring stations (Cambray, 1980; US Health and Safety Laboratory, 1977). Supplementary sources include reports on individual national measurements (Bonnyman et. al., 1972; Baltakmens and Gregory, 1977). The pattern of annual deposition at Australian stations has found the following principal features:

(i) first appearance of significant amounts of ^{137}Cs in 1955/56;

(ii) maximum fallout in 1963/64;

(iii) marked decrease in rate of deposition from 1959 until 1962, which appears as a minor maximum; and

(iv) perturbations due to Chinese and French atmospheric nuclear tests continuing until the late 1970s.

These factors are similar to those reported for other global stations (Ravera and Premazzi, 1971; Pennington et. al., 1973; Ashley and Moritz, 1979).

It is known that uptake of fallout by soils and sediments is rapid (Eyman and Kevern. 1975), and it follows that surface soil minerals have been labelled continuously at levels which depend on the prevailing concentration of ^{137}Cs in the total fallout. It must be remembered, however, that after the peak in fallout the integrated source function of ^{137}Cs does not follow the pattern of atmospheric fallout which has decreased dramatically (Stiller, 1979). Processes resulting from the overlaying of an original 1954 interface with sediment material lead to the formation of a ^{137}Cs concentration profile that relates to the annual variations in atmospheric fallout. The preservation of these structured concentration changes provides at least two time markers (dates of first appearance and maximum fallout) that are the basis of an absolute geochronology of these sediments.

4.3.2 Accuracy of ^{137}Cs dating techniques

The ^{137}Cs method is comparable with the ^{210}Pb and Ambrosia (ragweed) pollen grain techniques of Robbins et al. (1978). Within the experimental uncertainties, the sedimentation rates for the three methods are in good agreement. At low sedimentation rates, when the ^{137}Cs is located close to the surface, this technique is very sensitive to mixing or disturbance effects, including those brought out by the coring techniques.

4.3.3 Measurement of sediment redistribution with Cs-137

The transport and spatial distribution of sediments entering an impoundment are functions of the balance between the flow velocities, gravitational forces and the secondary forces of flow turbulence. In the case of reservoirs, drawdown procedures can be a very powerful initiator of sediment flows and redistribution. Three generalised zones of sedimentation are given for reservoirs (Wiebe and Drennan, 1973; for sedimentary process in lakes, see Sly, 1978):

(i) The upper zone in which complex deltas form as a result of flows entering the reservoir retaining their identity for some distance into the reservoir pool. The deltas grow outward by the formation of foreset (longitudinal flow) beds and upward through topset beds.

(ii) The intermediate zone in which the residual river velocity, waves and wave-induced currents transport and deposit most of the river's wash load, and some of the fine sediments eroded from the banks of the reservoir, to form bottom set beds of fine clays, silts and colloids.

(iii) The lower zone containing sediments eroded from the reservoir banks and transported by waves and wave-induced currents.

The relevance of these sediments classifications can be seen in the work of Simpson et al. (1976) in the Hudson River estuary, New York. They were able to classify three main types of distribution of ^{137}Cs in estuary sediment cores:

(a) Relatively low activities (19 mBq g^{-1*}) generally confined to the upper 5-10 cm of sediment and associated with subtidal banks.

(b) Higher activities than in (a) of about 90 mBq g^{-1} in the top 10 cm decreasing rapidly to about 7 mBq g^{-1} in the 10-15 cm layer and sometimes distributed down to 40 cm with an activity of about 1 mBq g^{-1}. This type of profile was interpreted as being indicative of a high sedimentation rate in a shallow protected environment.

(c) Profiles with variable but high activities of about 70 mBq g^{-1} down to 40 cm and, in one case, down to 250 cm. Caesium-137 activity below 40 cm was stated by Simpson et al. (1976) to be a clear indicator of rapid sediment accumulation. It is speculated that temporal changes in ^{137}Cs profiles along a transect at each of the three zones could be interpreted as changes due to redistribution or accretion in exactly the same way that McHenry and Bubenzer (1982) interpreted changes in field distribution of ^{137}Cs.

Perhaps the best example of the potential of the ^{137}Cs technique for this type of application is the Lake Michigan work of Plato and co-workers (Plato and Goldman, 1972; Plato, 1974; Plato and Jacobson, 1976).

The ability to interpret the structured concentration of ^{137}Cs in sediment is a very powerful aid in studying environmental influences.

4.3.4 Relationship between Trap Efficiency of a Reservoir/Lake and ^{137}Cs Loss from a Catchment

In the study of three small northern Mississippi catchments, Ritchie et al. (1974) presented in Table 11, which suggests that there is a relationship between the loss of ^{137}Cs from the catchment and the trap efficiency, particularly for the clay fraction. Such a relationship would provide another useful indicator for quantifying the impact of land uses on soil erosion and lake/ reservoir lifetime.

Table-11: Trap efficiency of a lake based on the activity of Cs-137 activity lost from a catchment and observed in the sediment deposited.

Data	Catchment		
	Forest	Grass	Grass-Crop
Ratio of ^{137}Cs loss from catchment and ^{137}Cs gain in Lake (%)	57.0	38.0	25.0
Measured sediment deposition (t/ha/year)	15.7	13.6	9.7
Trap efficiency (C/I) $= \frac{\text{reservoir capacity (C)}}{\text{annual inflow (I)}}$	0.24	0.20	0.12

4.3.5 Praticalities of the ^{137}Cs method

There are few details in the literature of the methods and rationale used by individual workers to obtain their samples. In taking a core sample there are three main difficulties:

(i) to avoid disturbing the very soft sediments in the upper 20 cm or so of the sedimentary sequence, yet be able to cope with a varying degree of compaction of the sediments with increasing depth (age). (The upper 20 cm region would include much of the ^{137}Cs data of interest).;

(ii) to overcome suction effects during removal of the core tube from the sediment bed, or from the outer casing of the coring device; and

(iii) to avoid compression or other disturbances of the core during penetration of the core tube into the sediment bed or extrusion of the core section which will give rise to serious errors in an accurate determination of the sediment-water interface or the true length of the core.

A Mackereth corer (Mackereth, 1958; Mackereth, 1969) or an adaptation of its design features, would provide a good working answer to these problems. However, it requires careful handling, since its fast return to the surface can be hazardous. The core tubes range up to 1 m in length, and generally have a diameter of 5 cm. The restricted diameter means that numerous cores have to be taken at each site to accumulate sufficient material for gamma spectrometry. Ritchie and McHenry (1978) collected eight cores per site and composited them by 10 cm increments. Where it is available, clear plastic rubbing, such as polycarbonate, is to be preferred as the integrity of the core can be appraised at the surface and the coring repeated if necessary (Brown, 1956).

Cores should be kept at or near in situ temperature to prevent expansion due to gas formation. Some organisations have available a cooled room for this purpose. Strong and Cordes (1976) have described a cloth sleeve filled with dry ice as a means of freezing cores. They reported that stratigraphic disturbance due to ice crystal formation did not appear to be a problem. If this or a similar cooling procedure is unavailable in the field, the cores have to be sectioned as soon as possible.

An alternative to hydraulic extrusion is to section the core tube carefully along the midline to enable one half to be removed entirely. Obviously a well consolidated sediment is necessary for this technique.

4.3.6 Gamma spectrometry

The analysis of ^{137}Cs by gamma spectrometry, using Ge(Li) or HyperPure Ge detectors, is relatively simple. The ^{137}Cs peak has an energy of 662 keV and the only interference is from a peak at 666 keV due to ^{214}Bi. This interference can be corrected by measuring the adjacent 609.3 keV peak, which is also due to ^{214}Bi, and applying a proportional correction to the sum of the 602 and 606 peaks (McCallan et al., 1980). The net peak area is proportional to the concentration of ^{137}Cs. The US National Bureau of Standards, Research Material b, homogeneous river sediment for radioactivity measurements, is available as a primary standard. When multi-element analysis is required, ^{137}Cs, Th, U and K standards can be prepared, using trisodium phosphate (12 H_2O) as the matrix (McHenry et al., 1973).

4.4 Collection of Sediment Cores from Lake Nainital and Dating

Twelve sediment core samples were collected (Feb. 95) from different locations in the Lake using a gravity corer, its inner and outer diameter being 5.0 and 6.0 cm respectively. Most of the sampling stations are from the eastern side of the Lake since a large number of gullies loaded with considerable amount of sediments join the Lake basin at those stations. The length of the cores obtained ranged in size from 15 to 60 cm. With a help of a adjustable piston rod with silicone packing, the obtained cores were extruded vertically and sliced at 2 cm intervals. Sliced core sections were stored in the laboratory. Measurements were made of the bulk density before drying samples in an oven at a temperature slightly above 100 °C for about 7 to 8 hours prior to analysis. The dry unit weight (expressed as the ratio of weight of dry sediment sample to total volume of the sliced core sample), water content (determined as the difference in weight between the wet sediment sample and dry sediment sample, and expressed as percent of the weight of the wet sediment sample), and porosity (calculated as ratio of volume of water in the sediment pores to total volume of the sliced core sample, and expressed in percent) were also estimated after drying. The textural composition of the core samples were mainly clay and silt. The clay mineralogy assemblage of this Lake mainly consists of montmorlionite, illite, kaolinite, and chlorite besides the mixed layer minerals, which are typical high altitude clays (Jauhari and Hashimi, 1994).

Out of the collected core samples, three cores (Q, S & V) which were considered to be representative and cover the maximum sedimentary environment of the lake (Fig. 1) were subjected to radiometric dating. The cores were sliced into 2 cm pieces and analysed at Bhabha Atomic Research Centre, Mumbai for ^{210}Pb and ^{137}Cs activities.

The determination of ^{210}Pb content is based on the α-measurement of its grand-daughter, namely ^{210}Po, which is assumed to be in secular equilibrium with its parent. The basic radiochemical procedure involves adding of ^{208}Po as a yield tracer, leaching the sediment samples with aqua regia, the residual solids were filtered off and the solution was dried and converted to chloride with concentrated HCl. The final solution was taken in 0.5 M HCl. Polonium nuclides were then spontaneously deposited on silver planchettes by adding ascorbic acid in the HCl solution prior to alpha counting using Si surface barrier detectors connected to a multi-channel analyser. The standard counting error was generally less than 10% in the upper sections of the cores and slightly higher values at the deeper sections since the counting time was kept constant for the entire core sections. As the supported ^{210}Pb results from the decay of ^{226}Ra present in the sediment core with which it is in equilibrium, estimation of ^{226}Ra activity was determined directly by gamma counting.

The ^{137}Cs activity in each section was determined at BARC, Mumbai, by gamma counting of the oven-dried samples using HyperPure Germanium detector coupled with a 4096 channel multichannel analyser system. A ^{137}Cs standard, having essentially the same geometry and density was used. The samples were counted for about 500 min to obtain good statistical accuracy. The detection limit for ^{137}Cs by this method is 0.25 mBq.g^{-1} and the standard counting error was less than 10% in the core sections.

As already discussed about three different models; such as CONSTANT FLUX and CONSTANT SEDIMENTATION RATE [CFCS], CONSTANT FLUX [CF] and CONSTANT INITIAL CONCENTRATION [CIC], that are being widely used for dating ^{210}Pb deposits with/without significant mixing during deposition (Krishnaswami and Lal, 1978; Crickmore et.al. 1990). However none of the models is universally applicabie (Eakins, 1983; Robbins and Edgington, 1975). In practice the type of model to be used is usually decided on the depthwise distribution of (total) ^{210}Pb concentration (Crickmore et.al. 1990). The estimated sediment accumulation rates in lake Nainital, using ^{210}Pb dating technique (both in linear and mass units), along with the ^{210}Pb models used, are given in Table 12.

Table 12. Sedimentation rates and inventories of ^{210}Pb and ^{137}Cs in Lake Nainital.

Sample (water depth in m)	Average sedimentation rate					Surfacial inventory***		
		^{210}Pb		^{137}Cs				
	model used*	linear (cm.a^{-1})	mass (g.cm^{-2}.a^{-1})	linear (cm.a^{-1})	mass (g.cm^{-2}.a$^{-1)}$	total ^{210}Pb	^{137}Cs	ratio
V (24)	CFCS	0.48± 0.04	0.112± 0.010	0.60±0.07	0.140±0.016	0.298	0.121	2.46
Q (20)	CF	0.64± 0.18	0.150± 0.041	0.70± 0.03	0.168± 0.007	1.059	0.161	6.62
S (20)	CF	1.24± 0.44	0.289± 0.104	1.35± 0.05	0.315± 0.018	1.525	0.260	5.87

** ^{210}Pb sedimentation rates (in linear and mass units) takes into the effect of compaction.

*** Surfacial inventories are in Bq.cm^{-2}. Note: ratio means total ^{210}Pb/^{137}Cs.

4.4.1 Pb-210 profiles in sediment cores

Krishnaswami and Lal (1978) have clearly mentioned the different pathways of ^{210}Pb to lake sediments. As seen in Fig. 4, at location V the (total) ^{210}Pb profile shows more or less an exponential decrease in concentration with depth to a constant value maintained by

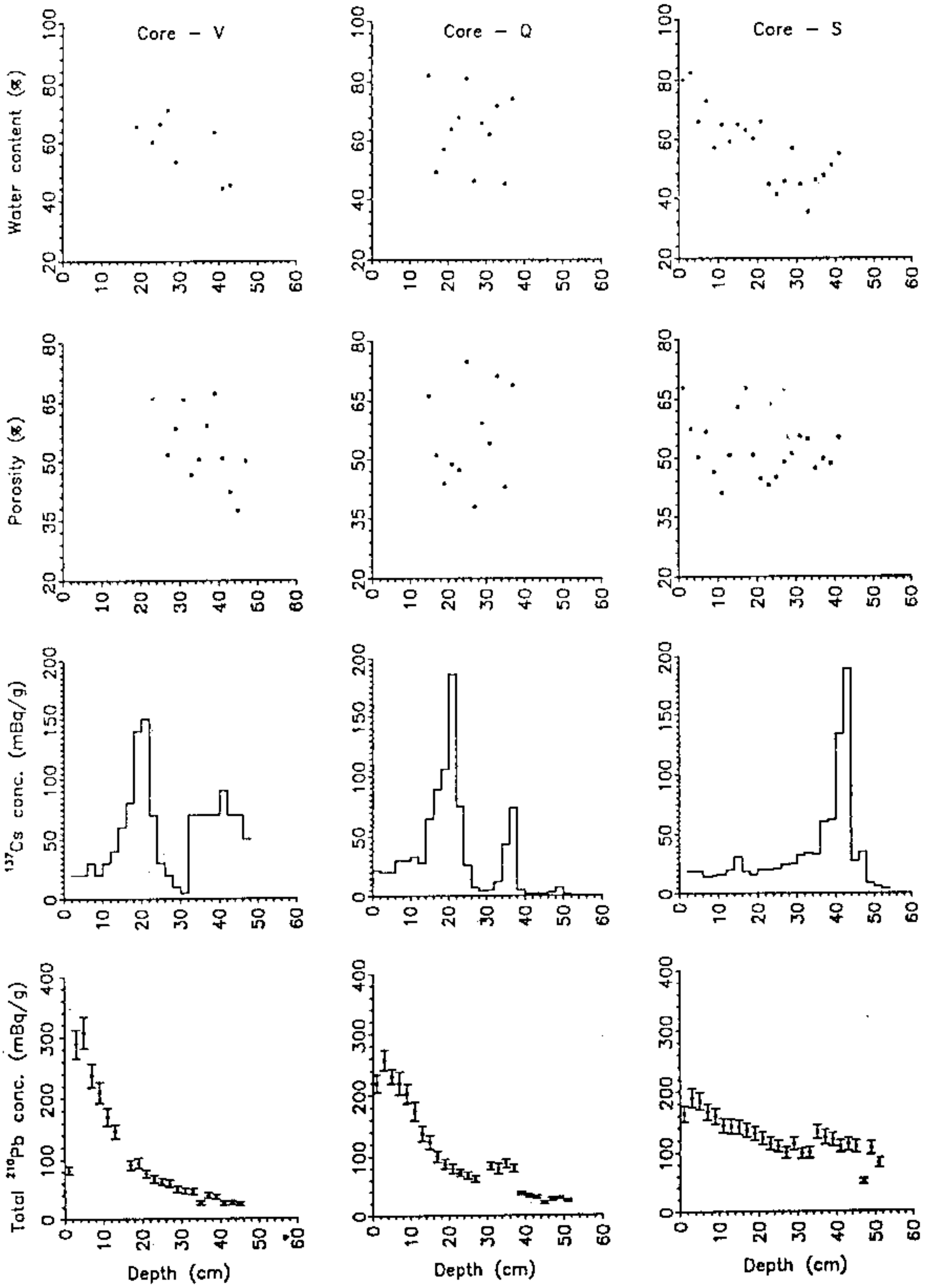

Fig. 4. ^{210}Pb and ^{137}Cs activity profiles in three core samples along with moisture content and density.

in situ decay of ^{226}Ra. At other locations the (total) ^{210}Pb concentration profile is not an exponential type (i.e., non-monotonic type). Companion measurement of ^{137}Cs indicated that the top portions of the sediment deposit were not lost during coring. The mean global atmospheric ^{210}Pb fallout is about 0.0165 Bq.cm^{-2}.a^{-1} (Krishnaswami and Lal, 1978) and therefore the mean atmospheric ^{210}Pb inventory should be about 0.529 Bq.cm^{-2}. In lake Nainital, the mean (total) ^{210}Pb inventory in the surfacial sediments of the sediment cores is slightly higher the global mean (i.e., about 0.961 Bq.cm^{-2}; Table 12). The atmospheric deposition flux of ^{210}Pb at the Lake is unknown, therefore the available mean ^{210}Pb atmospheric flux of Mumbai station, India (a value of 0.025 Bq.cm^{-2}.a^{-1}(Joshi et.al. 1969) and the inventory supported by this flux, I_{atm}, is about 0.802 Bq.cm^{-2}) may be assumed to be similar to lake Nainital area [the annual rainfall at Lake Nainital and at Mumbai is comparable and the difference in latitude is not large]. Thus it appears that the (total) ^{210}Pb supply to lake Nainital largely reflects the direct atmospheric fallout, however a further inventory of ^{210}Pb distribution over the Lake bottom must be made to properly assess the significance of other sources.

4.4.2 Residence time of Pb-210 in lake water

If Φ_w and Φ_s (Bq.cm^{-2}.a^{-1}) are the fluxes of ^{210}Pb in the Lake water and sediments respectively; their corresponding inventories I_w and I_s (Bq.cm^{-2}) can be derived using the first order kinetic relation as shown below:

$$dI_w/dt = \Phi_w - ([\lambda_{Pb} + (1/T_w)] \times I_w) \qquad (4)$$

$$dI_s/dt = \Phi_s - ([\lambda_{Pb} + (1/T_s)] \times I_s) \qquad (5)$$

where λ_{Pb} is the radioactive decay constant (=ln[2/22.3]a^{-1}), and T_w and T_s are the residence times of ^{210}Pb in the Lake water and Lake sediments, respectively. At steady state, the inventory of unsupported ^{210}Pb in the Lake water, I_w is the difference between the atmospherically supported inventory, I_a, [0.802 Bq.cm^{-2}], and the mean sedimentary unsupported ^{210}Pb inventory of the Lake, I_s [0.798 Bq.cm^{-2}]. Thus the relationship for the derivation of residence time of ^{210}Pb in Lake water, Tw, can be obtained from equations 4 and 5, with dI_w/dt and dI_s/dt = 0, as:

$$T_w = (I_a - I_s) / (\lambda_{Pb} \ I_s) \qquad (6)$$

since $\lambda_{Pb} << (1/T_w)$, $\lambda_{Pb}(1/T_s)$, and I_a - I_s. The residence time of ^{210}Pb in the Lake water calculated from equation (6) is about 2 months.

In a lake sediment core, a lower value of ^{210}Pb concentration at sediment-water interface compared to values at lower depths and/or a non-monotonic ^{210}Pb profile at any location may be attributable to: i) loss of surfacial sediments by slumping under existing slope of lake (Edgington et.al. 1991), (ii) sediment focusing of deposited sediments (Nozaki et.al. 1977; Brunskill et.al., 1984; Blais and Kalff, 1995), (iii) delayed input of sediments from catchment (Eakins, 1983), (iv) change in sediment accumulation rates (Schell and Nevissil, 1983), (v) varying sediment composition over whole of lake with dissimilar histories of deposition (Robbins and Edgington, 1975), (vi) dilution of accumulating sediments under probable events like land erosion/land slide etc. (Schell and Nevissi, 1983). and/or (vi) higher residence time of the radionuclide in lake water. In the following paragraph, based on the measured ^{210}Pb and ^{137}Cs concentrations in the lake Nainital sediment cores, along with their textural properties (like porosity and water content), an attempt has been made to identify and assess the effect of the above said factors (i.e. slumping, sediment focusing, delayed input, dilution, inhomogeneity in the sediment composition etc.) on the ^{210}Pb (and ^{137}Cs) profiles in the Lake core samples.

Among the various factors mentioned above, the mobility due to bioturbation, higher residence time of radionuclide in lake water, and delayed input of sediments from catchment may not be true for the observed lower sediment-water interfacial ^{210}Pb (at locations Q and S) of lake Nainital. This is because of the prevailing anoxic conditions at the Lake bottom (Jauhari and Hashmi, 1994) which inhibits any major biological activities to bring significant bioturbation, and the shorter residence time (2-3 months, as calculated above). Further, the grain-size analysis of the Lake bottom sediments indicate poorly sorted grains (0.98-1.03 phi) pointing to near-distance transportation of material (Das et.al. 1993). Therefore the non-monotonic ^{210}Pb profiles (at locations Q and S), and a lower sediment-water interfacial ^{210}Pb concentration (at all locations) in this Lake could be due to a physical phenomenon (like sediment focusing, slumping, due to dilution by the silt in a, possible, event like land erosion/land slide etc.), and/or due to actual change in the sediment accumulation rates with varying sediment composition and histories of deposition. Sediment focusing is a process whereby water turbulence moves sedimented material from shallower to deeper zones of a lake. Based on Hakanson's scheme (Hakanson, 1977; Blais and Kalff, 1995), an attempt has been made to identify if there is any sediment focusing taking place in the core sampling locations of the Lake. According to Hakanson's scheme, 50% water content of surfacial sediments in a lake sediment core marks the transition between zone of erosion and transportation, and 75% water content of surfacial sediments marks the transition between zone of transportation and accumulation. However as it can be seen from Fig. 2, the surfacial water content in the core sediments of lake Nainital is above 75% and therefore there is no sediment taking place in the sampling location of the Lake.

The porosity profile for homogeneous sediments with uniform compaction usually show an exponential decrease with depth (Athy, 1930). But in lake Nainital, the porosity profiles are not exponential type (Fig. 4). Also the Lake bottom slopes gently at the sampling locations and do not favour any major slumping. This probably indicates that the non-monotonic ^{210}Pb profiles (at locations Q and S) and/or a lower sediment-water interfacial ^{210}Pb concentration (at all locations) in lake Nainital is the result of the actual change in the sedimentation rate with varying sediment composition and dissimilar histories of deposition.

The surfacial inventories of (total) ^{210}Pb and ^{137}Cs and their ratio in lake Nainital are given in Table 12. The inventories of unsupported ^{210}Pb are 0.205, 0.935, and 1.247 Bq.cm^{-2} at locations V, Q and S respectively, and their corresponding ^{137}Cs inventories are 0.121, 0.160, and 0.260 Bq.cm^{-2}. Leland and Shukla (1973), in a study to know the factors affecting distribution of lead and other trace elements in sediments of Lake Michigan, concluded that organic matter is more important in the complexation of lead in lake water and sediments than absorption on clays on hydrous oxides. On the other hand, the dominant mechanism of ion-exchange with the clay component of sediment and soils results in the removal of ^{137}Cs from the water column (Jenne and Wahlberg, 1968). Therefore, the observed spatial distribution of ^{137}Cs and (total) ^{210}Pb in the sediments of lake Nainital may reflect patterns of deposition of two major sedimentary components, clay and organic carbon respectively.

There is a strong correlation between the sedimentation rate and inventories of both the nuclides in the Lake. In Tallital basin of the Lake, it appears that ^{210}Pb/^{137}Cs is lower away from the shore and higher close to the shore. This again substantiates our earlier finding of the dissimilar particle associations or histories of deposition of these two nuclides, namely ^{210}Pb and ^{137}Cs. Therefore the non-monotonic ^{210}Pb profiles in the Lake may be the result of varying sedimentation rates and sediment composition with different histories of deposition and is less likely due to the post-depositional redistribution of sediments in the lake.

A non-uniform sedimentation rates at locations V, Q and S in the Lake probably indicates that the Lake has different deposition zones, with comparatively higher sedimentation rates in Tallital basin (i.e. locations V and S) than in Mallital basin (i.e. location Q). Within Tallital basin, the sedimentation rate at location S is higher than at location V. Thus it appears that there is a general trend in the sedimentation rate in the Lake with a decreasing value from nearshore to farshore. However this needs to be verified with a few more core samples along a cross-section in the Lake. The results indicate that in all core sampling locations in the Lake, the short-term rates (for the last three decades) derived from ^{137}Cs, an anthropogenic nuclide, is marginally high compared to long-term (last 120 to 150 years) rates deduced from environmental ^{210}Pb. This may be due to the fact that the insignificant mixing and redistribution of accumulating sediments has a more effect on a short-term estimate rather than on a long-term estimate. Study on the effect of compaction, attempted for core V, indicated that the effect of compaction is to decrease the sediment accumulation rate compared to original value.

The estimated sedimentation rates are within the range of values (i.e. 0.1 to 40 cm.a^{-1}) reported for a number of other lakes by Krishnaswami and Lal (1978). At the same time it is interesting to note that the sediment accumulation rates in lake Nainital is comparatively higher than in other lakes of this region (Das et.al., 1993). This is because lake Nainital is surrounded by carbonate rock which is highly susceptible to weathering and high precipitation in the region (annual Average is 250 cm) also reflected in high TDS content (average being 440 mg/L), low vegetative cover around the Lake due to anthropogenic activities, etc.

4.4.3 Cs-137 profile in sediment cores

At sampling location Q in the Lake, the ^{137}Cs profile (Fig. 4) closely parallels its weapon fall-out record pattern reported by earlier investigators like McHenry et.al. (1973), Livingston and Cambray (1978) etc. (i.e. an initial appearance in 1952-'53; a subsidiary peak in 1957-'58; and a major peak in 1963-'64). With depth corresponding to 1963-'64 as time marker, Average sedimentation rate (both in linear and mass units) of lake Nainital is listed in Table 12.

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 must still be viewed as an ideal case, as there have been many studies in which ^{137}Cs profile in a lake sediment core does not closely match that associated with the fallout record mainly due to post-depositional mobility of ^{137}Cs resulting from bioturbation (Sholkovitz and Mann, 1984), molecular diffusion (Davis et.al., 1984), "sediment focusing" i.e. resuspension of deposited sediments in shallower zones by waves and water currents with subsequent transport to and settling in deeper zones (Brunskill et.al., 1984; Blais and Kalff, 1995), higher residence time of ^{137}Cs in lake waters (Edgington et.al., 1991), and influence of delayed inputs of radiocesium from drainage basin of a lake (Miller and Heit, 1986). Due to short length of the core obtained and/or due to higher sedimentation rates (Table 12), the initiation and subsidiary peaks of 1952-'53 and 1957-'58 are not clearly seen at core samples V and S respectively (Fig. 4).

4.4.4 Sedimentation rates in lake Nainital

About 150 samples, belonging to the three sediment cores, have been analysed. These cores were collected from the north and south sub-basins of the lake which covers deepest, middle portions and also zones near to the banks. The sedimentation rate obtained by ^{210}Pb in different parts of the lake varies from 0.48 cm/yr to 1.24 cm/yr. In case of ^{137}Cs, it varies between 0.60 cm/yr and 1.35 cm/yr (Table 13).

Table 13: 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	

† Das et al. (1994)

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 (Table 14) with that obtained by sediment balance method.

Table 14: Average sediment accumulation rate in lake Nainital and lake life estimated by different methods in the present study

Method of Estimation	Average rate of sediment accumulation		Lake Life (years)
	m^3/yr	cm/yr	
Sediment Balance	3175	0.69	2681
^{210}Pb dating	3460	0.75	2480
^{137}Cs dating	3970	0.86	2160

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.

5.0 COMPUTATION OF LIFE OF LAKE NAINITAL

As already discussed under section 4.3.3, the inflow velocity and other forces such as gravitational force and the secondary forces of flow turbulence control the spatial distribution of incoming sediments in lakes. 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.

As mentioned above, the lake has been divided into four zones for ^{210}Pb (Zone I, IIa, IIb and III) and into three zones (I, II and III) for ^{137}Cs on the basis of geomorphology, bathymetry and spatial variation in the sedimentation rates (Fig. 5). The quantity of sediment received by each zone has been computed, by multiplying the sedimentation rate with the area of that zone. The total volume of the lake divided by the volume of sediment received by the lake annually, gives the lake life.

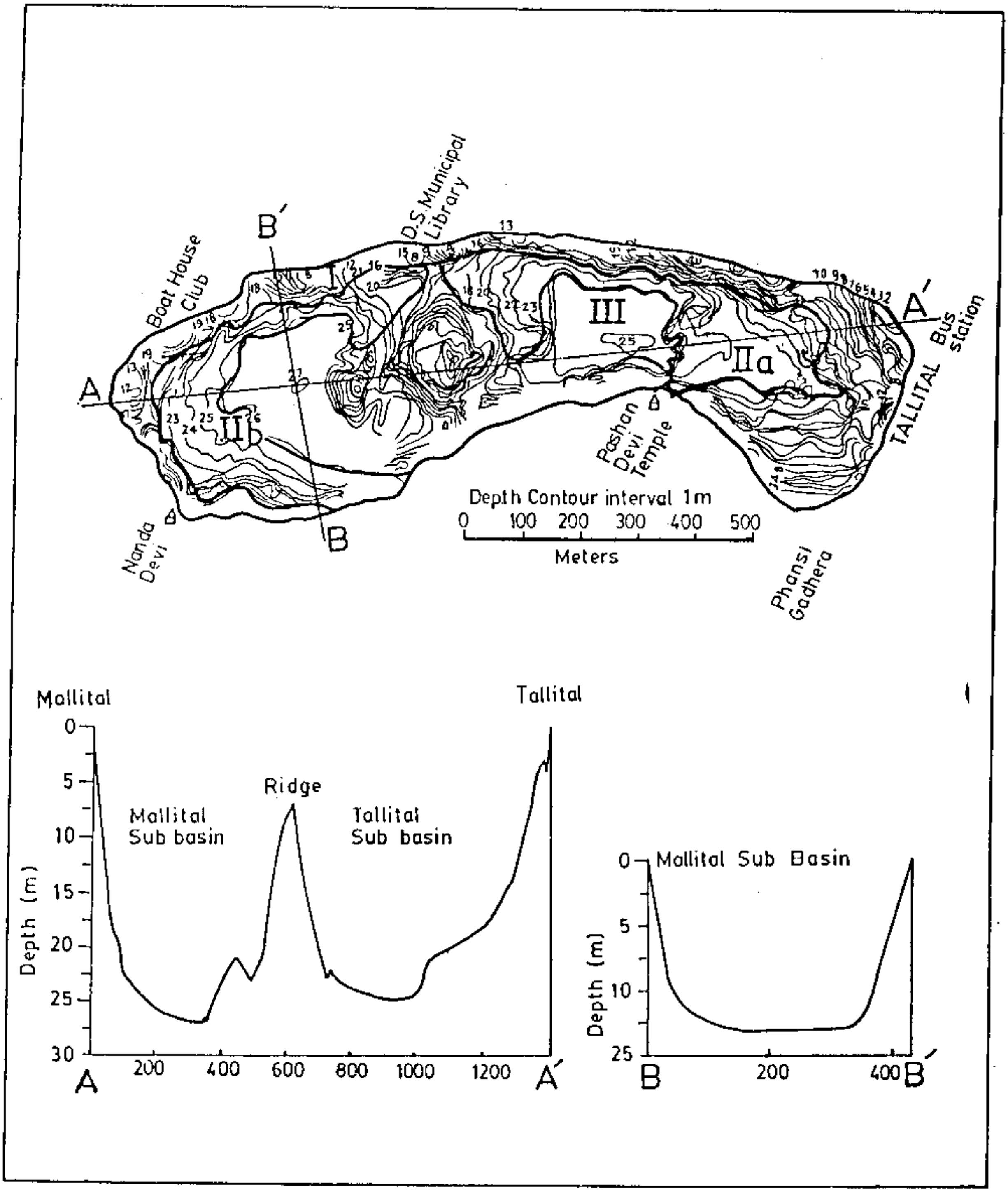

Fig. 5. Four different depositional zones of Lake Nainital with the cross sections showing the present bottom configuration of the lake.

The life of Nainital lake has been computed by using results obtained by conventional and radiometric dating techniques.

5.1 Life Using Conventional Techniques

In conventional techniques, the lake sounding data of different time periods have been used to estimate the lake life. The selected periods of interval are three years, five years,, ten years and fifteen years as per details presented in Table 15. The life of lake Nainital varies from 39 to 221 years if computed by taking sounding data for 3 to 5 years time interval but, it comes 395 years if period of interval taken from 5 to 11 years. However, the lake life comes to be 590 years if determined by taking 15 years period of interval from 1960 to 1975 while sedimentation rate is varying from 0.038 to 0.113 million cubic meter per year. It clearly indicates that validity of predicted lake life is very less significant due to errors in the lake sounding data collected by a very crude method. The life of the lake has been also predicted from 300 to 400 years by the previous investigators is based on the lake sounding (manual) data, the validity of which has already been questioned.

Table 15: Estimated life of Nainital lake and rate of sedimentation based on P.W.D. sounding data.

Selected Period	Rate of Sedimentation Mm^3/yr	Lake Life in Years
1960-1965	0.038	221
1965-1970	0.113	75
1972-1975	0.084	101
1990-1993	0.218	39
1990-1996	0.057	149
1960-1975	0.014	590
1985-1996	0.021	395

Hukku et al.(1968) estimated the lake life as 82 years on the basis of 1960-1966 sounding data. Sharma (1981) predicted the life to be 314 years using 1960 and 1975 sounding data. Rawat (1987) compared 1895, 1969 and 1979 lake volume and estimated the lake life as 380 years. The method adopted by the above investigators and their data source are presented in Table 16.

In the present study, an attempt has also been made to critically analyse the UPPWD sounding data. Figure 5 illustrates large variations in the silting rate i.e. from 0.107 Mm^3 $year^{-1}$ to 0.02 Mm^3 $year^{-1}$ in the lake in the past 45 years period. The data also indicates an overall scouring in the lake during certain five years span (0.101 $Mm^3 year^{-1}$ to 0.047 Mm^3 $year^{-1}$) while there is no surface outflow from the lake for the larger part of the year and the sluices installed at the southeastern end of the lake are opened only during monsoon season (June-September) to maintain the lake level. In addition to this, the lake remains stratified during the rainy season and only the epilimnion water having the suspended sediment concentration of 0.47 g l^{-1} is drained out through the sluices.

However, for an instance, if one assumes that the scouring does take place, in the period 1955-60, the sediment scoured out will be of the order of 181115 metric tonnes (1.78 g cc^{-1}, dry density). It means that the rate of sediment outflow should have been 36.4 g l^{-1} for the mean rainfall of 203 cm in the catchment and 50% direct runoff. This rate is high and unrealistic for the lake environment, implying that the validity of sounding data is questionable. Therefore, the lake volume has been computed using the lake sounding data for every 5th year, starting from 1960 (Fig. 6a), which indicates that during certain time periods there has been an overall increase in the volume of the lake. This may probably be due to the lake bottom subsidence. However, there is no recorded evidence supporting the subsidence of lake bottom, including the recent publication of Valdiya (1988) which discusses the structural geology of the area in great detail. The increase in the volume could also be due to the discharge of an equivalent volume of sediment from the lake. Figure 6b shows the volume of sediment accumulated in or scoured out from the lake during different periods, calculated using both Average end area and contour methods. If we assume that scouring does take place then the sediment concentration in the outflow should be about 40 g/l, a value obtained using the annual rainfall - surface outflow relationship for Lake Nainital (Fig. 7).

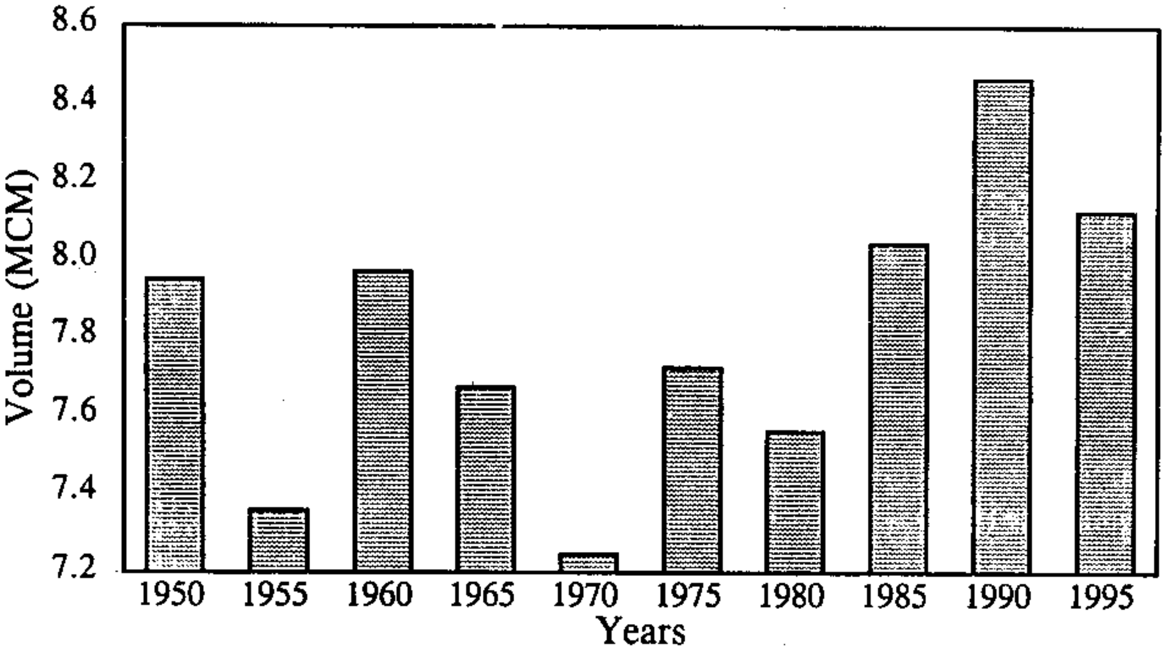

Fig. 6a. Volume of the lake based on the silting and scouring rates obtained in Lake Nainital computed for different time periods since 1960 using lake sounding data.

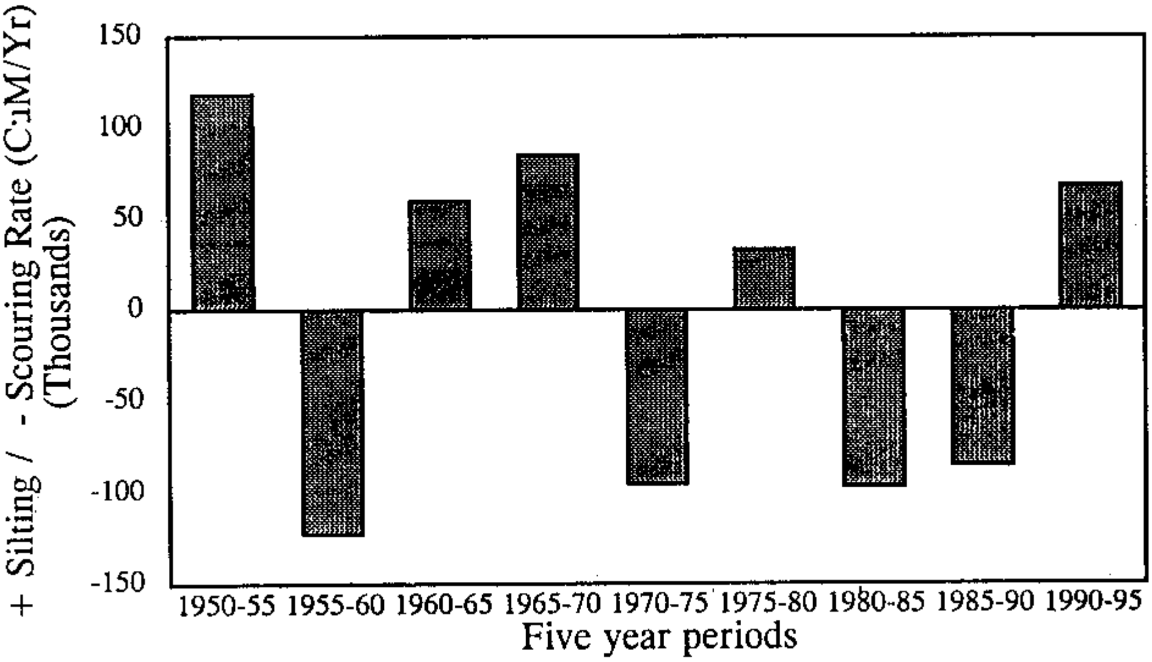

Fig. 6b. Volume of sediments accumulated in or scoured out based on the silting and scouring rates obtained in Lake Nainital computed for different time periods since 1950 using lake sounding data.

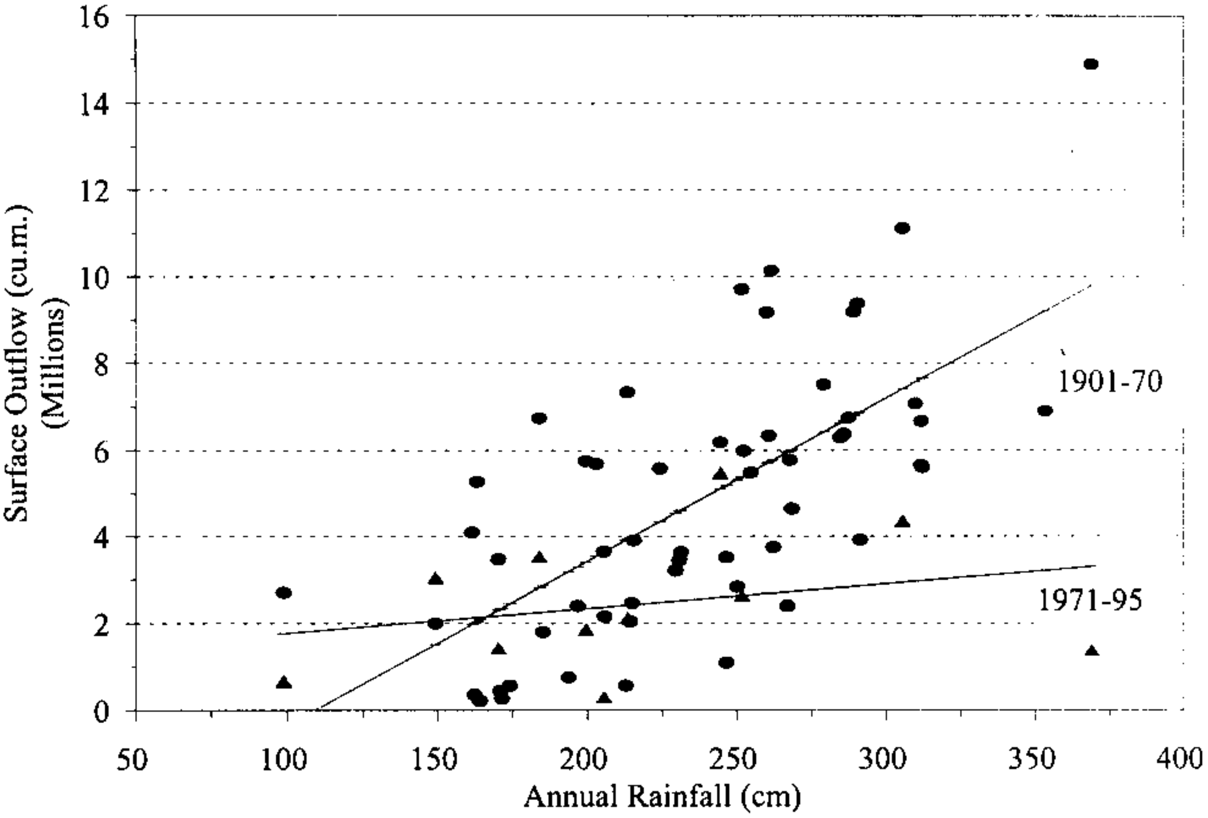

Fig. 7. Annual rainfall - surface outflow relationship for Lake Nainital, worked out using long-term hydrological data. (Lower slope during 1971-95 due to increased pumping from lake)

But, the Average sediment concentration in the lake outflow (0.55 g/l) does not support the scouring theory.

The life of lake Nainital is also estimated using sediment balance method which comes out nearly 2681 years.

5.2 Life Using Radiometric techniques

Both ^{210}Pb and ^{137}Cs geochronological dating are powerful techniques for determining recent sediment accumulation rates. However, the use of ^{137}Cs for dating is comparatively limited than ^{210}Pb method as ^{137}Cs could be effectively only for post-bomb events. The ^{210}Pb data determined by Das et al. (1994) at one location (D, Fig. 1) has also been used for the computation of lake life in the present study.

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 (Table 16). 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 15) of earlier investigators.

However, this life has been determined if the deposition of the sediments etc. near the banks and drains opening is ignored, i. e., this deposition can be easily removed every year as per the practices being followed presently. However, the life estimated using the radiometric data available presently is surprisingly high than ever estimated by other investigators in the past using conventional techniques. Das et al.(1993) has determined the rate of sediment deposition near the off shore as 1.1 cm/year which is very close to the data obtained presently.

The comparison of the life of Nainital Lake determined by various investigators using different methods, including the radiometric method used in the present case, is given below in Tables 16.

Table 16: Life of lake Nainital estimated using lake sounding methods by previous investigators and comparison with the values obtained presently by the authors.

Data Used	Period Selected for Study	Method of Estimation	Predicted Life (Year)	Investigators
Lake Sounding	1960-1966	Mean siltation and Area	82	Hukku et al. (1966)
Lake Sounding	1965-1975	-do-	314	Sharma (1981)
Lake Sounding	1895,1969 &1979	Contour	380	Rawat (1987)
Sediment Radioactivity	na	^{137}Cs ^{210}Pb	2163±77 2479±312	Present study
Suspended Sediment	na	Sediment Balance	2681	Present study

6.0 CONCLUSIONS

The rates and pattern of recent sediment accumulation in Lake Nainital through ^{210}Pb and ^{137}Cs geochronological dating methods have been used for the prediction of the lake's life. The life thus estimated is much higher than the ones predicted by earlier investigators using bathymetric data. Therefore, the sediment balance method was used to counter-check the validity of the results. The sediment accumulation rates obtained by radiometric dating technique compare very well with sediment balance method. Thorough analysis of long term bathymetric data reveals that the data may not be useful for any quantitative predictions, because of improper recording of depth at different points and no verification procedures have been followed.

Most of the conclusions are based on the limited number of cores analyzed to date. It appears that the lake is not shallowing at a rate reported by earlier investigations. The possibility exists that the Lake is still subsiding approximately at the same rate it receives the sediments (Jauhari and Hashmi, 1994). It seems that the Lake has different depositional zones with constant/varying recent sedimentation rates. The sedimentation rate at Tallital basin is comparatively higher than at Mallital basin. The residence time of both ^{210}Pb and ^{137}Cs in the Lake waters is very short. Varying sedimentation rates and sediment composition with different histories of deposition can account for the observed non-monotonic ^{210} profiles at certain locations and for comparatively less ^{210}Pb concentration and ^{137}Cs in the basins of the lake are intriguing and raise questions as to their sources, transport, and fate, and by implication, the fate of contaminants with similar chemical properties.

Using the sediment accumulation rates obtained through radiometric dating methods the full life of Lake Nainital is estimated as about 2200 years. The case of Lake Nainital is a typical example of how even a seemingly reliable long term sounding data could be misleading. Therefore, when the information on life of a surface water body becomes an important and sensitive issue, the sediment accumulation rates may be estimated accurately using radiometric dating techniques. 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, render the validity of complete sounding data questionable.

^{210}Pb and ^{137}Cs geochronological dating is a valid and powerful technique for determining recent sediment accumulation rates and pattern in Lake Nainital. However the use of ^{137}Cs for dating is considerably more limited than the ^{210}Pb method and can be undertaken only where the sedimentation rate is sufficiently high to be compatible with inherent sampling resolution.

Further, the following conclusions may be drawn in general from the present study.

a) For the estimation of lake life, the sediment accumulation rates should be known accurately. Sedimentation rates obtained through lake sounding data collected without mechanical or electronic positioning systems may often be misleading. Care should also be taken to use the same sounding weight or rod every time, to minimise the errors.

b) Sedimentation rates determined through radiometric dating techniques provide precise data and it is also cost effective as it needs one time sampling only.

c) Although the results arrived should relieve the Nainital community and administrators of their apprehension about the life of Lake Nainital, installation of new sediment traps and better management of existing ones along the drains, will increase the life of the lake.

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